

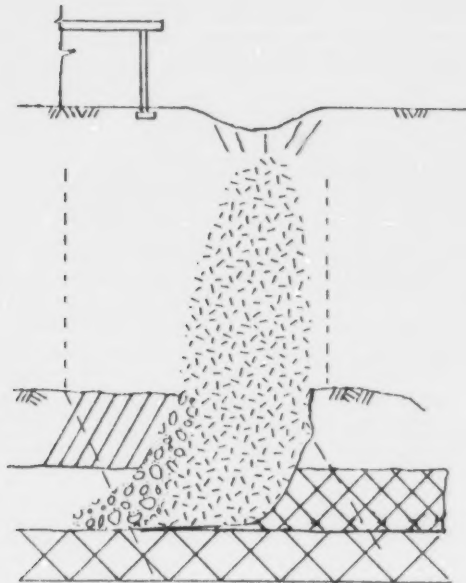
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LES MINES SELBAIE

COMPLETE RECOVERY OF SURFACE CROWN PILLARS AT LES MINES SELBAIE, QUÉBEC



Phase V Final Report - DESIGN EVALUATION

CANMET/MRL Energy, Mines and Resources Canada

DSS File: 03SQ.23440-7-9195

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SELBAIE



STRATA ENGINEERING CORP.

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July 23, 1991

S-87-198

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Re: Phase V Final Report - DESIGN EVALUATION - COMPLETE RECOVERY OF
SURFACE CROWN PILLARS AT LES MINES SELBAIE, QUÉBEC
CANMET/MRL Energy, Mines and Resources Canada
DSS File: 03SQ.23440-7-9195

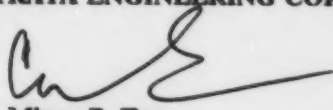
Dear Sir:

We are pleased to submit our Final Report on Phase V, "Design Evaluation" in fulfilment of Les Mines Selbaie's contract with CANMET and DSS under the captioned contract.

We trust you will find the report satisfactory and complete in its coverage of all of the items discussed at various meetings and by telephone over the last 12 months.

We thank Les Mines Selbaie for their cooperation and assistance in the preparation of this report and for their guidance in the field work and design evaluation. We thank you most sincerely for your constructive comments and suggestions, without which this report may not have achieved the high standard that we feel it now represents.

Yours very truly,
STRATA ENGINEERING CORP.


C. Mirza, P. Eng.
Project Manager

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COMPLETE RECOVERY OF SURFACE CROWN PILLARS

AT LES MINES SELBAIE, QUÉBEC

Phase V - DESIGN EVALUATION

CANMET / Energy, Mines and Resources Canada

DSS File: O3SQ.23440-7-9195

1.0 INTRODUCTION

The soils overlying the surface crown pillars at Les Mines Selbaie, near Joutel, Québec, comprise a series of weakly cohesive but very dense till-like sands and silts, some 40 m in thickness. The surface crown pillars consist of kaolinized, soil-like, extensively altered weak rock with highly enriched ore values. For such weak soil-like rock masses, conventional methods of analysis of surface crown pillar stability, such as those used in hard rock mining, are inapplicable. Hence, research was necessary to determine safe and economical methods of surface crown pillar recovery without removal of the overlying soils and without causing disturbance to surface facilities.

In 1985, research was sponsored by CANMET into the development and validation of a weak rock mass model for the safe support of the surface crown pillars at Les Mines Selbaie. The contract was awarded to C. Mirza Engineering Inc. (later amalgamated with Strata Engineering Corp.). In 1988, a follow-up research contract was awarded to Les Mines Selbaie, with Strata Engineering Corp. as sub-consultants, to investigate the feasibility and economics of complete recovery of the surface crown pillars without removal of the overlying soils. This is the first time that proactive research into the complete removal of surface crown pillars and actual such safe and beneficial extraction has been performed at a Canadian mine site. It required geomechanical characterization of the rock and overlying soil masses as well as numerical modelling, instrumentation, monitoring, model verification and economic analyses.

This report summarizes the research work at Les Mines Selbaie and evaluates the results obtained. It also contains recommendations and guidelines for use in the proposed recovery of surface crown pillars at other mine sites. The submission of this report fulfils the requirements of Phase V of the research contract between CANMET and Les Mines Selbaie.

2.0 PREVIOUS STUDIES

Research into the characterization and behaviour of weak soil-like rock masses comprising the surface crown pillars at Les Mines Selbaie was initiated by CANMET in 1985. It was recognized that unusually high ore values were to be found in this upper weaker zone of the mine workings and that current methods for design of stopes in such weak materials were inadequate for the ground conditions being encountered during trial mining. Therefore, a research project, under DSS File: 15SQ.23440-5-9017, was initiated into the "Sampling, Field Testing and Modelling of a Surface Crown Pillar at Les Mines Selbaie". The results of the ensuing research were published in the following reports under the general heading of: "Weak Rock Mass Model for Support of Surface Crown Pillar at Les Mines Selbaie":

- **Phase I - Drilling, Sampling & Laboratory Testing**

Issued by: C. Mirza Engineering Inc., August 21, 1986 [Vol. 1 - Report; Vol. 2 - Appendix]

- **Phase 2 - Model Development and Model Calibration**

Issued by: Strata Engineering Corp., November 30, 1987

- **Phase 3 - Instrumentation for Ground Control**

Issued by: Strata Engineering Corp., September 30, 1988

These initial studies indicated that complete recovery of the surface crown pillars, without removal of the overlying soils (the overburden), was feasible provided the stability charts created were used, together with appropriate soil and weak rock mass behaviour models. These charts, along with rock mass sampling methods, modelling and instrumentation were all developed for the first time for seriously altered surface crown pillar rock masses.

A research proposal was submitted by Les Mines Selbaie to CANMET (DSS File: 03SQ.23440-7-9195) to recover the surface crown pillars by the control caving method of mining. The ensuing research contract was divided into five phases. The reports for each phase of the research and actual recovery are as follows:

- **Phase I - Analytical Feasibility**
Report issued by: Strata Engineering Corp., June 22, 1988
- **Phase II - Laboratory and Field Testing for Final Numerical Analysis**
Report issued by: Strata Engineering Corp., June 6, 1990 [combined with Phase IV Report]
- **Phase III - Economic Feasibility (in French)**
Report issued by: Les Mines Selbaie, March 30, 1989
- **Phase IV - Monitoring of Field Trial**
Report issued by: Strata Engineering Corp., June 6, 1990 [combined with Phase II Report]

This report is submitted for:

- **Phase V - Design Evaluation**

In this report, the objectives of the research program are cited in Chapter 3. Geomechanical data for the overlying soils and surface crown rock pillars at the Les Mines Selbaie site are given in Chapter 4. A review of surface crown pillars is given in Chapter 5, followed by general extraction methods, considered and used by the Mine, in Chapter 6. Basic design methods and concepts are described in Chapter 7. Numerical modelling studies are described in Chapter 8. The ore recoveries and economical benefits are described in Chapter 9, which also contains a description and history of cave-ins. Chapter 10 contains major conclusions derived from this research program.

In Chapters 11 and 12, recommendations are given in the form of guidelines for possible application of the results of this research at other mine sites where a complete recovery of the surface crown pillars, without removal of the overlying soils, may be under consideration. General guidance is provided to serve as a check list of key factors for use in design and implementation of the proposed recovery program.

3.0 RESEARCH OBJECTIVES

The objectives of Phase V, "Design Evaluation", are:

1. To evaluate the approaches, methods, solutions, remedial measures and equipment used in the project so as to be informative firstly on a technical basis, but also to be exhaustive for transfer of technology to mine operators.

Details pertaining to this objective are given in Chapter 10.

2. To compare numerical/analytical prediction methods with actual field behaviour, comparing all aspects such as: times and shapes of overburden caving, general soil behaviour, subsidence, effect of remedial measures, and the like.

Chapters 4 to 9 inclusive discuss the techniques used in achieving this objective.

3. To make recommendations for recovery of surface crown pillars and soil caving at other mine sites, including the effects of overburden thickness, variations in soil types and of surface crown pillar (opening) spans, and difficulties relating to extraction of the surface crown pillar masses.

Recommendations which satisfy this objective are contained in Chapter 11.

The primary objective of this Design Evaluation report is to provide general guidance for the complete recovery of surface crown pillars, without removal of a variety of overburden soil types. The use of these guidelines at other mines requires the full and knowledgeable consideration of appropriate soil and rock mass behaviour characteristics, mining methods, and failure mechanisms. Methods of mining and risks associated with the safety of surface structures and facilities must also be considered in designing an ore recovery program specific to the mine site. Direct technology transfer should not be attempted unless tempered with judgement and prior experience. The particular characteristics, special situations and prevailing conditions at a given mine site will require a conscious and detailed evaluation of the appropriateness of application of the guidelines given in Chapter 11 of this report.

4.0 GEOMECHANICAL DATA

This chapter summarizes information on the geology, field investigations, laboratory testing, instrumentation, and performance monitoring at the Les Mines Selbaie site. The subsurface conditions, ore body characteristics, geomechanical data, instrumentation, and monitoring of field trials are described in some detail. It should be recognized that the results obtained are specific to the prevailing physical soil and rock mass characteristics, operating conditions and mining methods used at this Mine site. These procedures may need to be modified to suit prevailing conditions and surface crown pillar mining methods at other mine sites.

4.1 Site and Geology of Les Mines Selbaie

Les Mines Selbaie is a 1650 tonnes per day (tpd) polymetallic (copper-zinc-gold-silver) mine located in northwestern Québec, approximately 60km northwest of Joutel and 40km east of the Ontario/Québec provincial boundary (see Figure 1a and Plate I). The ore body is located within the Chibougamou-Matagami section of the Abitibi volcanic belt. The geology of this area has been documented (Bouillon, 1990; Chauvin, 1977; Deptuck et al., 1982; Sinclair and Gasparrani, 1979).

An open pit mine has been developed since 1985. It is located approximately 1.2km east of the existing underground mine, and produces 5800 tpd (Caron, 1990, Personal Communication). The relationship between the underground and open pit mines is shown in Figure 1b and Plate II (Bouillon, 1990). The B-Zone of the Mine is situated in a tabular ore body dipping at 50°, and associated with a northeasterly striking fault consisting of quartz-sulphide vein systems up to 200mm wide, occurring within several elongate lenses of heavily fractured rock, up to 30m in width, in the hanging wall of the fault.

The bedrock of this area consists of a series of tuffs and breccia, bedded chert-pyrite and volcanoclastic debris located near the southwestern margin of a plutonic complex known as the Brouillan Granite. The rock immediately surrounding the fault zone is characterized by pulverized sulphide and shattered quartz veins (Plate III). The fault and open fractures have apparently provided an excellent channel for descending meteoritic water. As a result, supergene alteration (Sinclair and Gasparrani, 1979) has enriched ore values as far down as the 200m depth level.

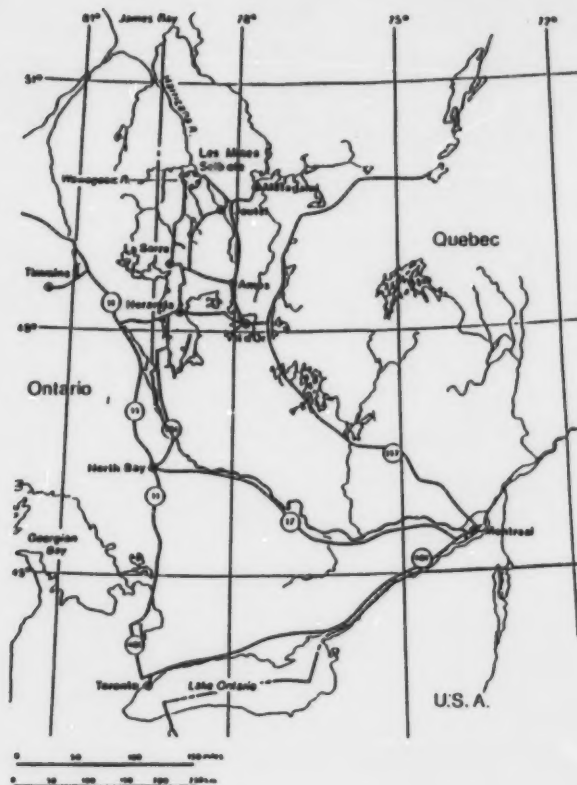


Figure 1a. Site Location, Les Mines Selbaie

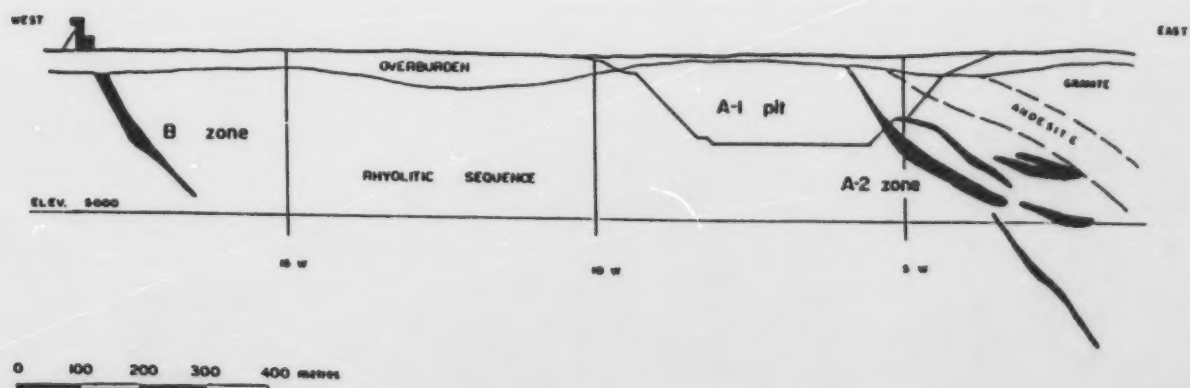


Figure 1b. B zone of Les Mines Selbaie

At the start of 1989, the minable ore reserves in the B zone of the Mine were just over 925,000 tonnes, averaging 0.96 g/t of gold, 30.78 g/t of silver, 3.51 % copper, and 0.32 % zinc (Bouillon, 1990).

The overburden soils above the B zone are some 40 m thick and comprise non-cohesive to slightly cohesive or plastic silty to sandy glacial tills and glacio-fluvial deposits, generally of a very dense character. A cohesive clayey formation known as the Cochrane Till is found in some parts of the mine site, but not in the overburden soils above the B zone.

4.2 Ore Body Characterization

The geological structure and the characteristics of the rock mass of the crown pillar at Les Mines Selbaie have been described by Arjang (1983, 1984). The ore body is composed of three types of materials: rock-like; soil-like; and infill material.

The rock-like materials comprise about 70 per cent of the ore body by volume. They consist of dacite tuff (Plate V) and highly decomposed and kaolinized dacite tuff breccia (Plate VI). The breccia contains lenses of moderately decomposed quartz and faintly to highly decomposed chalcocite and chalcopyrite (Plate VII). The soil-like rock mass comprises about 30 per cent by volume of the ore body and consists of gravel sized angular pieces of ore and native rock in a clayey silt to sandy silt fine grained soil matrix (Plate VIII). It includes stringers of decomposed sooty chalcocite (Plate IX) and highly to completely decomposed kaolinized dacite tuff breccia (Plate X). The infill materials generally comprise grey fine sands and silts, found mostly near the contact with the overburden (see Plate IV). The infill materials and highly altered weak rocks constitute zones of weakness within the surface crown pillar rock mass.

4.3 Site Investigations

The physical and engineering properties of the overburden soils and the weak crown pillar rock mass at Les Mines Selbaie were determined from the following field investigations:

- drilling and sampling three boreholes in 1985-86;
- pressuremeter testing in two additional boreholes during 1988;
- piezometer installation and monitoring of groundwater levels;

The appended drawing shows the location of boreholes, the ore body and mine facilities. The overburden stratigraphy is shown in Figure 2. The field investigation incorporated innovative drilling and coring techniques to overcome core recovery problems in the altered weak soil-like rocks (Bétournay et al., 1988). Typical examples of cores recovered from two boreholes are shown in Plates XI and XII.

Two boreholes were drilled and sampled between July 12 and 21, 1988. One borehole was located above Stope 2 and one above Stope 5, and were drilled respectively to final depths of 24.4 m and 46.9 m above Stopes 2 and 5. Standard Penetration Resistance Tests were performed at frequent intervals and samples recovered in the split-barrel sampler, the accompanying N values being noted in blows/0.3 m.

From underground scanline surveys (see Plate IV), laboratory testing, and field measurements, a Quick Field Classification system (QFC system) was developed for the evaluation of the in situ weak rock and soil-like rock materials in the Mine, as shown in Table 1. The QFC System (Table 1) was developed specifically for the types of materials found at Les Mines Selbaie. It may not be applicable to other mine sites. Good correlation was found with certain index properties, as shown in Figures 3 and 4.

The QFC was a convenient system for the qualitative assessment of the surface crown pillar rock mass at Les Mines Selbaie. Other systems could also have been used. Recently, Juang (1990) has proposed a methodology based on fuzzy set theory to establish a performance index for the Unified Rock Classification System, or URCS (Williamson, 1984). The proposed method provides a tool for dealing with qualitative methods of rock mass classification, such as the URCS. Fuzzy set theory offers an opportunity for rationalizing qualitative assessment of rock mass characteristics in situations where established rock classification systems, such as those proposed by Barton et al. (1974), Bieniawski (1979), and Skinner (1988), may not be applicable.

Some physical and engineering properties of the surface crown pillar rocks and the overburden soil mass at Les Mines Selbaie are given in Table 2.

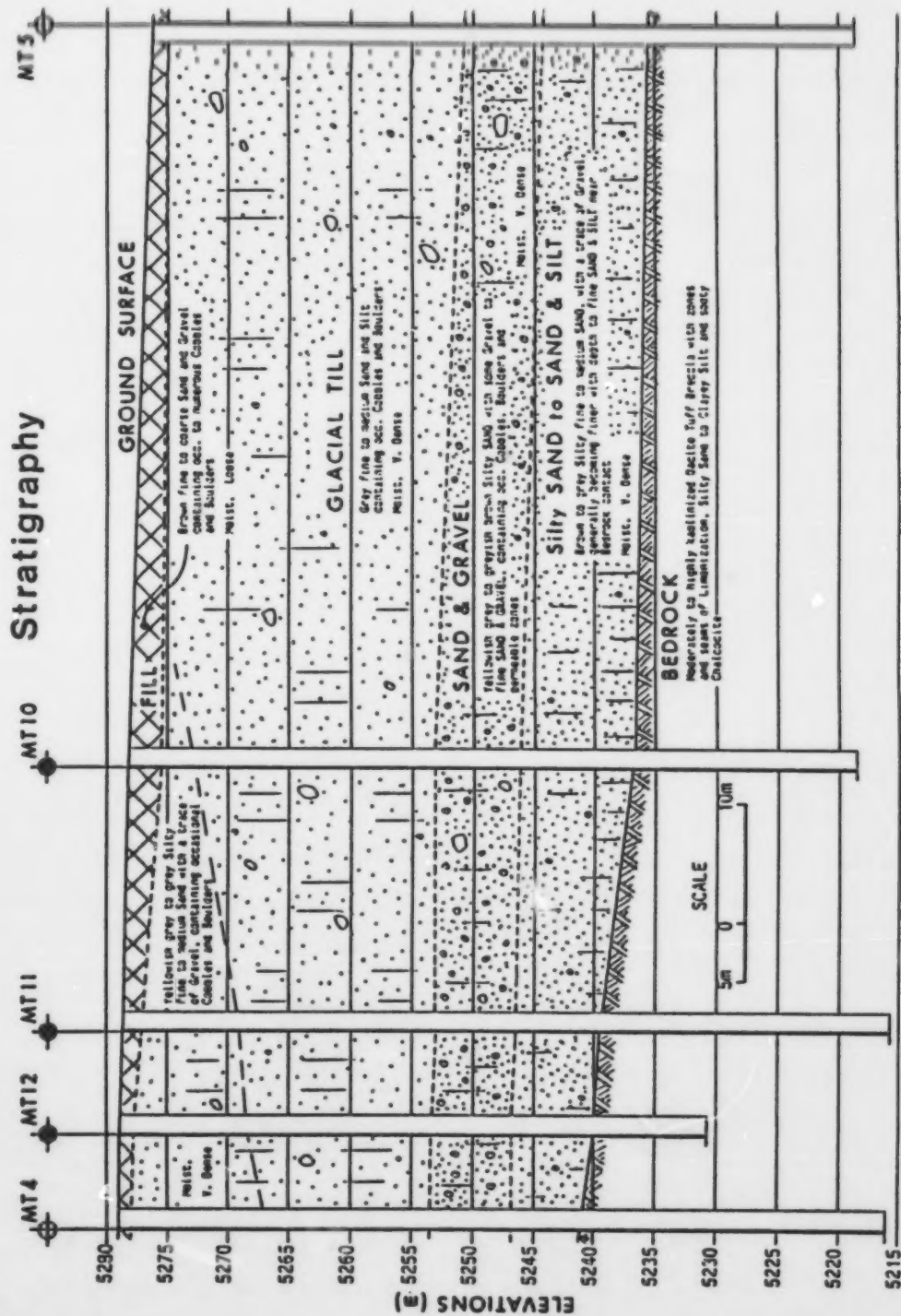


Figure 2. Section of overlying soils above orebody

Table 1 Quick Field Classification¹ of Rock Mass at Les Mines Selbaie

Rank	Characterization of Rock Mass	Field Determination of Relative Strength	Average Volume (%)
1	Very Strong	>1 Hammer blow to break	9.7
2	Strong	1 Hammer blow to break	17.4
3	Mod. Strong	5mm indentation with pick	12.4
4	Mod. Weak	Cannot be cut by hand	6.3
5	Weak	Crumbles under firm blows with pick	14.1
6	Very Weak	Broken in hand w/ difficulty	9.4
7	Very Stiff	Indented by fingernail	6.6
8	Stiff	Not moulded by fingers	5.7
9	Firm	Difficult moulding w/ fingers	7.2
10	Soft	Easily moulded by fingers	10.4
11	Very Soft	Squeezable between fingers	0.8

1. Developed by John Blair, P. Eng., in cooperation with the Mine's Chief Geologist, Mr. J. J. Bouillon.

Table 2 Key Properties of Surface Crown Pillar Materials at Les Mines Selbale

Property*	Overburden	Rock Type		
	(Soil Mass)	Soil-Like	Weak Rock	Strong Rock
Thickness (m)	37.5 - 41.3			
Volume (%)		30	40	30
QFC Rank		7 - 11	3 - 6	1 - 2
w (%)	6 - 12	5 - 25		
w _L (%)	NP	19 - 25		
PI(%)	NP	1 - 7		
γ (kN/m ³)	22.6 - 23.1	18.6 - 25.9	25.6 - 33.0	27.0
I ₂ (%)		68.9 - 98.3		
ϕ' (°)	34.7 - 35.2	40.6 - 40.9		
c' (kPa)	0	0		
<u>Compressive Strength (MPa)</u>				
Point Load		2 - 5	3 - 48	106 - 288
Schmidt Hammer		23 - 36	47	
Penetrometer		0 - 7		
Unconfined		0.1 - 0.6	2 - 36	69 - 308
<u>Modulus of Elasticity (MPa)</u>				
Tangent		0 - 0.02	12 - 24	28

* Abbreviations

w = natural moisture content; w_L = Liquid Limit; PI = Plasticity Index; NP = Non-plastic;

γ = unit weight;

I₂ = Slake Durability Index; ϕ' = effective angle of internal friction;

c' = effective cohesion intercept;

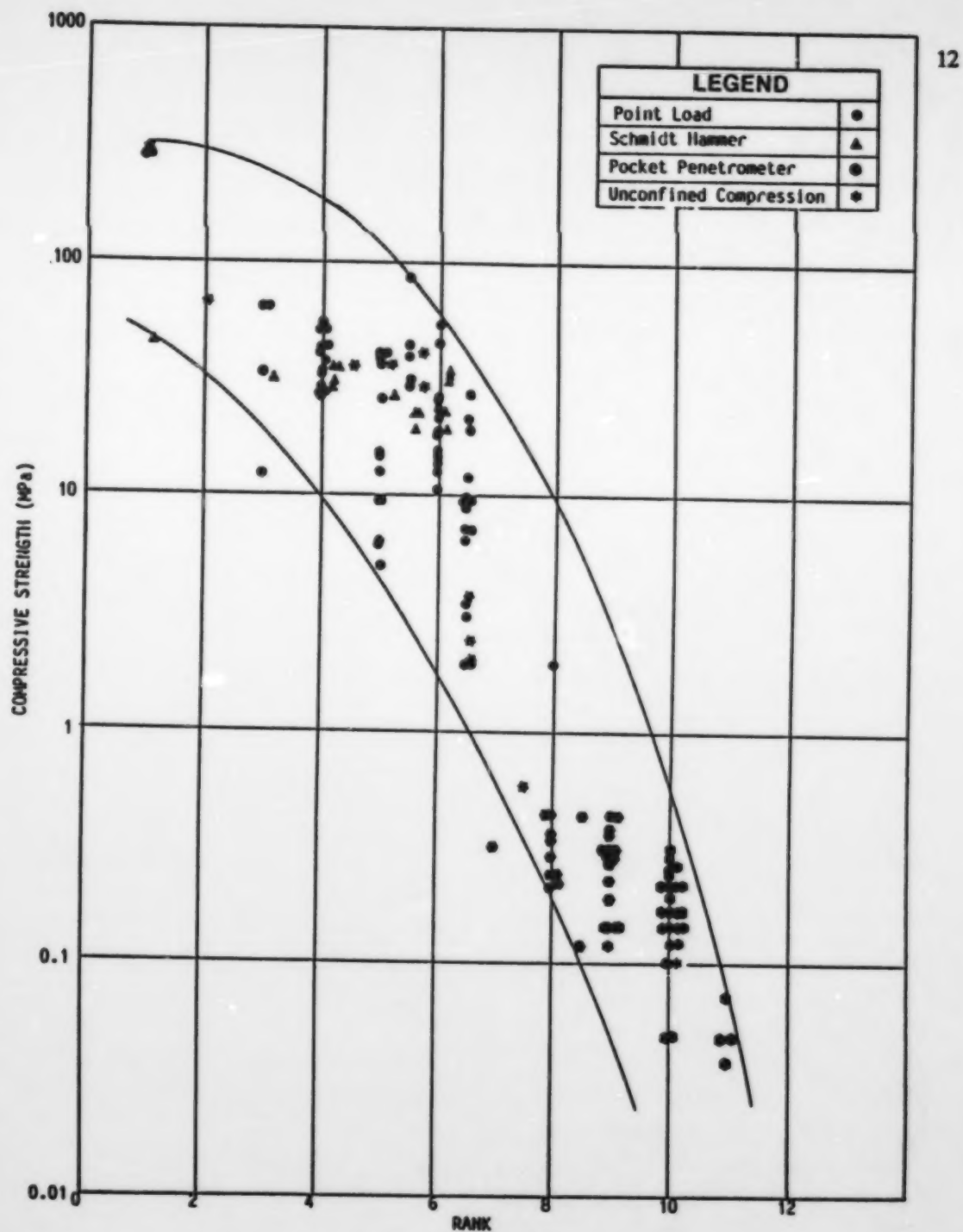


Figure 3.

Quick Field Classification vs. Compressive Strengths

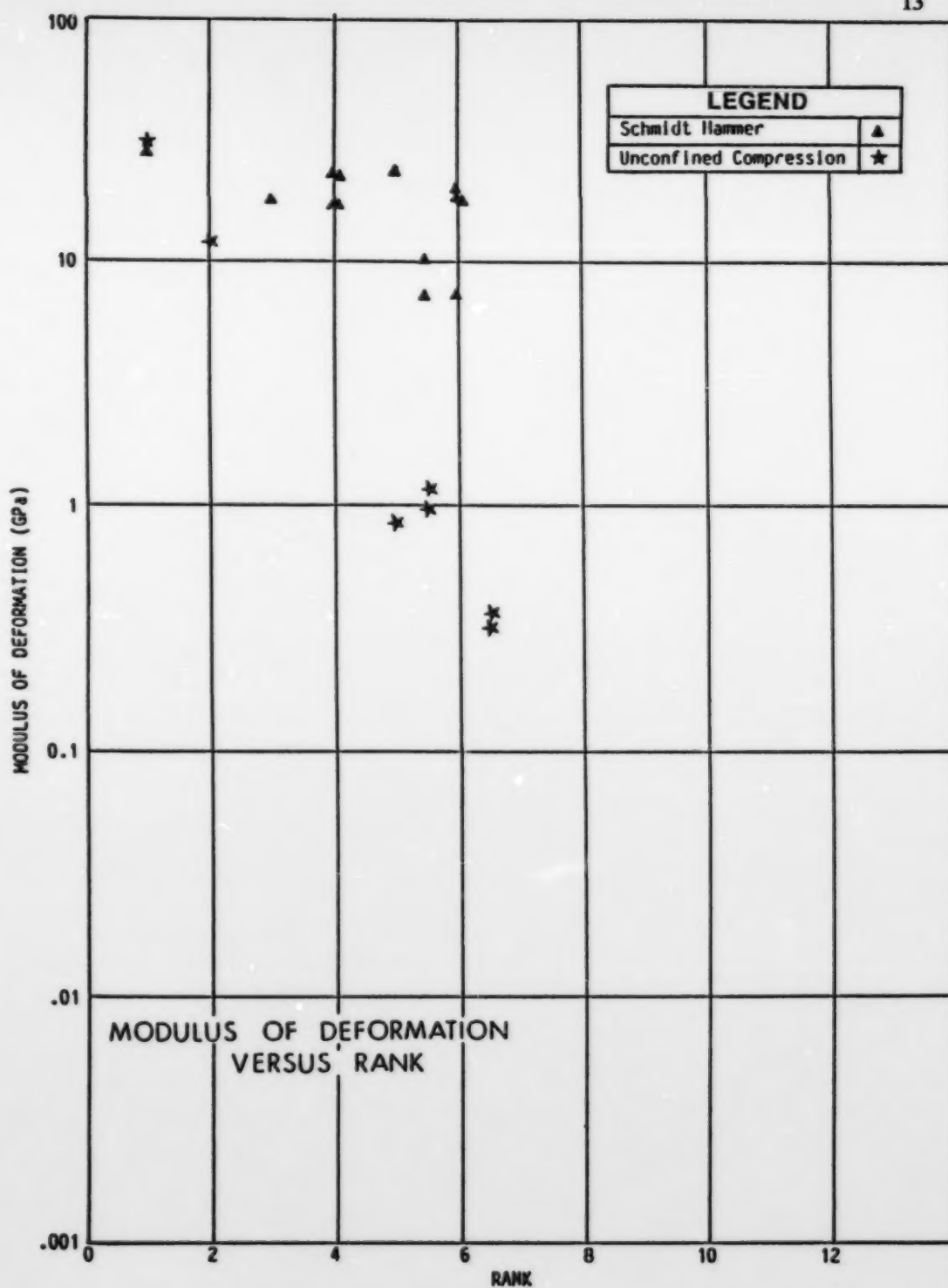


Figure 4

Quick Field Classification vs. Modulus of Deformation

4.4 In Situ Testing

The geomechanical characteristics of the rock mass were determined both by laboratory tests on representative field samples and, where possible, in situ. The deformation properties of the ore body at the 55 m level of Les Mines Selbaie were initially determined by pressuremeter tests. The pressuremeter had dimensions of 1 m in length by 115 mm in diameter (Herget, 1981; Swan and Vaillancourt, 1983). Eight tests were conducted along the borehole. Assuming a Poisson's ratio, ν , of 0.4, the deformation modulus values calculated from this testing program ranged between 280 kPa and 2,460 kPa.

In 1987, a dilatometer test was conducted in Borehole MT 11 at the 55 m level. Using $\nu = 0.4$, the deformation modulus was calculated to be 140 kPa. For the silty sand overburden at the 37.5 m level in Borehole MT 12, a deformation modulus of 39 kPa was obtained.

In 1988, pressuremeter tests were conducted at generally 3.0 m intervals of depth and from these, values of the modulus of elasticity ranging from about 50 kPa near the surface to over 100 kPa at depth were obtained. In the weathered weak rock mass the modulus value was just over 50 kPa, whereas in the sound rock, the modulus was nearly 800 kPa (Monterval, 1988). The large range and variation with depth of the deformation moduli probably indicates the absence of a consistent pattern in the occurrence of the kaolinization within the ore rock mass.

The Standard Penetration Resistance Test (SPT) N values in the overburden were, in all cases, in excess of 100 blows/0.3 m, indicating the soils overlying the surface crown pillars to be very dense. It should be recognized that the presence of cobbles and boulders within the soil matrix could lead to higher N values than would otherwise be the case. Therefore, all SPT tests should be monitored by a geotechnical engineer experienced in their interpretation.

4.5 Rock Joints

Since rock joints play an important role in the overall behaviour of surface crown pillars, their shear properties were estimated by CANMET (Swan, 1984) from predictive models. Ten block samples with a minimum dimension of 0.2m x 0.5m, each featuring a selected joint surface, were obtained from the Mine. The model described in Komornik et al. (1970) was used for the estimation of the shear properties of the rock joints (Strata Engineering Corp., 1987).

4.6 Field Stresses

Field stresses in a rock mass indicate the degree of anisotropy which must be accounted for in analytical and numerical modelling. The stress regime in a rock mass may be determined by overcoring. In this technique, a small diameter pilot hole is drilled at the stress measurement location. An instrument capable of measuring strains is inserted into this pilot hole. Then, an oversize drill bit is used to overcore around the instrument within the pilot hole. During overcoring, the instrument placed within the pilot hole responds to strains caused by stress relief. Field stress determinations by overcoring were made with a CSIRO hollow inclusion triaxial strain cell. Tests were conducted by CANMET (Arjang, 1984) at the 70 m, 180 m and the 290 m levels of Les Mines Selbaie. In general, the horizontal stress was found to be higher than the vertical stress (Strata Engineering Corp., 1987).

4.7 Monitoring of Field Trials

In one of the boreholes, drilled under Phase II of this research contract, a system of ground subsidence monitoring using a magnetic probe extensometer was installed (Strata Engineering Corp., 1990). The purpose of this installation was to monitor potential settlements below the ground surface and within the overburden soil mass upon removal of the surface crown pillars.

Surface monuments were erected above and around the various stope workings. Ordinary theodolite levels were shot on these monuments at frequent intervals, using a Mine geodetic bench mark datum for all readings.

Adjacent to stopes to be blasted, 25 mm diameter PVC pipes were installed in vertical holes within the overburden to monitor lateral ground movements. The ease of travel of rigid straight 12 mm diameter rods of different lengths into the 25 mm diameter pipe gives a qualitative measure of lateral ground deformation. As the ground deflects, the entry of the rods into the host 25 mm pipe becomes difficult. By using different lengths of straight rigid rods, one can estimate the depth at which deflections are occurring. The technique is qualitative, and very imprecise compared with slope indicator installations.

When cave-ins occur, the opening at the surface is immediately mapped and recorded, with an estimate made of the shape of the funnel or chimney (Plate XIII).

Detailed records are kept by the Mine of the blasting and mining techniques used in each stope. Detailed surveys are made using laser equipment to map the shape of the blasted opening. The tonnage of ore recovered from each blast and stope are recorded, and the ore dilution is monitored for each ore draw. An example of the records kept by the Mine is given in the Appendix.

The field monitoring work was found to be extremely helpful in calibrating models used in predicting surface cave-ins (Strata Engineering Corp., 1990).

4.8 Instrumentation

In order to validate predictive models, it was necessary to develop an instrument capable of detecting and measuring surface crown pillar and overburden deflections before, during, and after blasting of a stope. Consideration of several readily available types of instruments, both mechanical and electrical or electronic, showed these would not be suitable due to potential for breakage during blasting and due to reasons of inaccessibility after blasting.

Therefore, a mechanical device was fabricated at the Mine using a 50 mm diameter dial gauge as the primary movement indication device (Strata Engineering Corp., 1988). The mechanical instrument measures deflections at the surface crown pillar relative to a fixed point some 8m to 10m above the crown pillar, as shown in Figure 5 and Plate XV. Plate VXI shows an installed unit. The grouted collar assembly deflects with the surface crown pillar. The dial gauge records the magnitude of the deflection by reacting against the fixed horizontal steel plate attached to the central cable bolt and stabilized by means of four springs. The absolute movement of the crown pillar can be obtained by subtracting the ground movement at the surface from the total dial gauge movement. This simple and economical deflection monitoring instrument was extremely useful in calibrating the predictive models used in the design of safe stope openings. Net displacements in the order of 1 mm to 7 mm were registered.

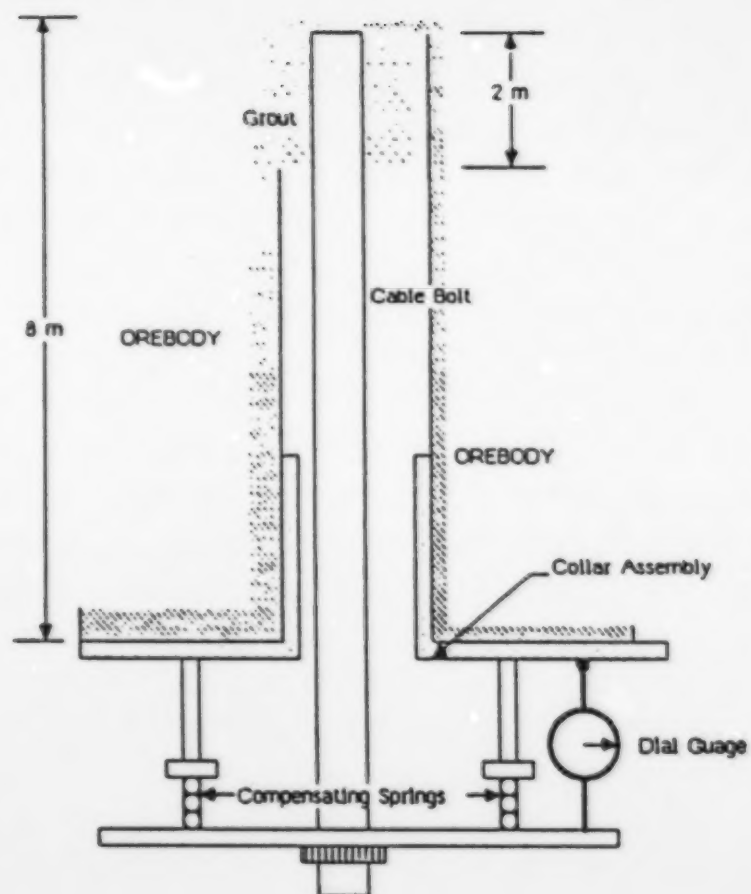


Figure 5. Instrument to Measure Surface Crown Pillar Deflection

5.0 SURFACE CROWN PILLARS - A REVIEW

The purpose of this chapter is to familiarize the reader with a subject of emerging interest in the Canadian mining industry. It provides an overview of the state-of-the-art concerning surface crown pillars and describes in some detail the surface crown pillars at Les Mines Selbaie. Various design processes and methods currently in use are described and discussed.

5.1 General

Surface crown pillars of the type being studied in this project are that class which are located in mines with near surface deposits (0 m to 100 m). They are distinct from conventional deeper underground pillars.

Information concerning this subject is limited. Major sources of information are case studies by Bétournay (1986, 1987) and Bétournay et al. (1987). The purpose of surface crown pillars may be said to be as follows (Bétournay, 1986, 1989):

1. To protect miners from surface elements such as bodies of water, soil and precipitation;
2. To prevent pillar elements from interfering with mining activity due to water inflow, surface subsidence, soil removal and rock removal due to sloughing;
3. To keep the extraction economical.

In general, the unique attributes of surface crown pillars are:

- The designer must deal with unsuitable materials which can not be substituted, and must often deal with dimensions and loads which can not be altered.
- Usually low values of lateral stresses occur near the surface which, given the altered and jointed characteristic of surface crown pillar rock masses, can not be relied upon to contribute to stability. Therefore, gravitational forces and structural integrity play a major role in design.

5.2 Surface Crown Pillars at Les Mines Selbaie

The surface crown pillars for which this research was undertaken are located in the B zone of Les Mines Selbaie. The B zone geology is dominated by tectonic breccia along the main fault zone. Multiple episodes of brecciation are said to be evident (Bouillon, 1990). The fault matrices are mineralized. The rock fragments in the fault breccia are moderately to extensively kaolinized. In general, the B zone is characterized by extensive lensing, more or less parallel to the main ore body which dips at an average of 50°.

The main lens (which is some 500 m in length at the 180 m level) has a variable width (10 m to 40 m). Complicating this variability and dispersion of the ore is the degree and extent of kaolinization, which is extensive at the ore-rock/soil-overburden contact. The intensity of kaolinization decreases with depth, until below the 200 m level, no kaolinization occurs.

The overburden thickness is about 40 m on average (Figure 2). The ore material immediately below the overburden is extensively kaolinized and the rock mass characteristic is that of a soil containing boulders or cobbles. The analogy of cherries embedded within a cheesecake matrix is appropriate for the conditions found from 15 m to 30 m below the overburden-ore body contact.

The original crown pillar at the Mine was located between the 100 m level and the overburden contact. A residual pillar of 7.5 m thickness was left in place at the contact for later recovery (Plate XVII). The overburden contact delineation was performed by the Mine in the early stages of development by drilling on a 10 m by 10 m pattern (Fourmanoit, 1990). Drilling was performed from below in 50 mm and 100 mm diameter holes to assist with drainage of the overburden. Drifts were driven at the 55 m level, some 7.5 m from the contact.

To achieve recovery, the old backfill was removed at the 55 m level to gain access to the base of the residual surface crown pillar. A slot raise was advanced upwards, and 75 mm diameter holes were used for drilling and blasting of the remainder of the stope. A 1.0 m zone immediately below the overburden contact was left in place. During drilling and blasting in the kaolinized zones, damping of vibrations was significant (Fourmanoit, 1990). The degree of kaolinization affected rock mass strength (Hoek, 1983) and the time to failure.

In plastic soils, stress relief by unloading (such as by removal of ore) causes the pore water pressure between clay particles to become negative, temporarily increasing the shear strength. With the passage of time the pore water pressure within the clay matrix returns to normal. This is accompanied by a "loss" in strength. This type of time dependent strength reduction can cause a block of material to fail under normal gravitational forces. This failure mechanism, progressing along the hanging wall at Les Mines Selbaie, has caused several failures to, and including, the overlying soil in a chimney fashion.

In non-plastic or non-cohesive soils, such as silts and sands, the pore water pressures reduce or rise considerably faster than in clayey type cohesive soils, due to their higher inherent permeability. Hence, time delay mechanisms are not normally associated with non-plastic types of soil.

At Les Mines Selbaie, the rock mass within the upper 15 m of the surface crown pillar zone represents a worst case scenario. The material is neither rock (due to soil infilling and kaolinization), nor soil (due to the presence of blocks of rock within a slightly cohesive matrix). Therefore, the assessment and simulation of the behaviour of such a material requires special investigative and testing techniques.

5.3 Design Process

Bétournay (1989) suggests an integral design process for the design of surface crown pillars. Briefly, this integral process consists of ten basic steps (Figure 6):

1. Identification of the deposit and regional rock characteristics
2. Geotechnical investigation
3. Establishing mining strategy and advance
4. Data analysis
5. Design methods and initial/final dimensions
6. Mining activity
7. Monitoring
8. Back analysis
9. Recovery
10. Design evaluation

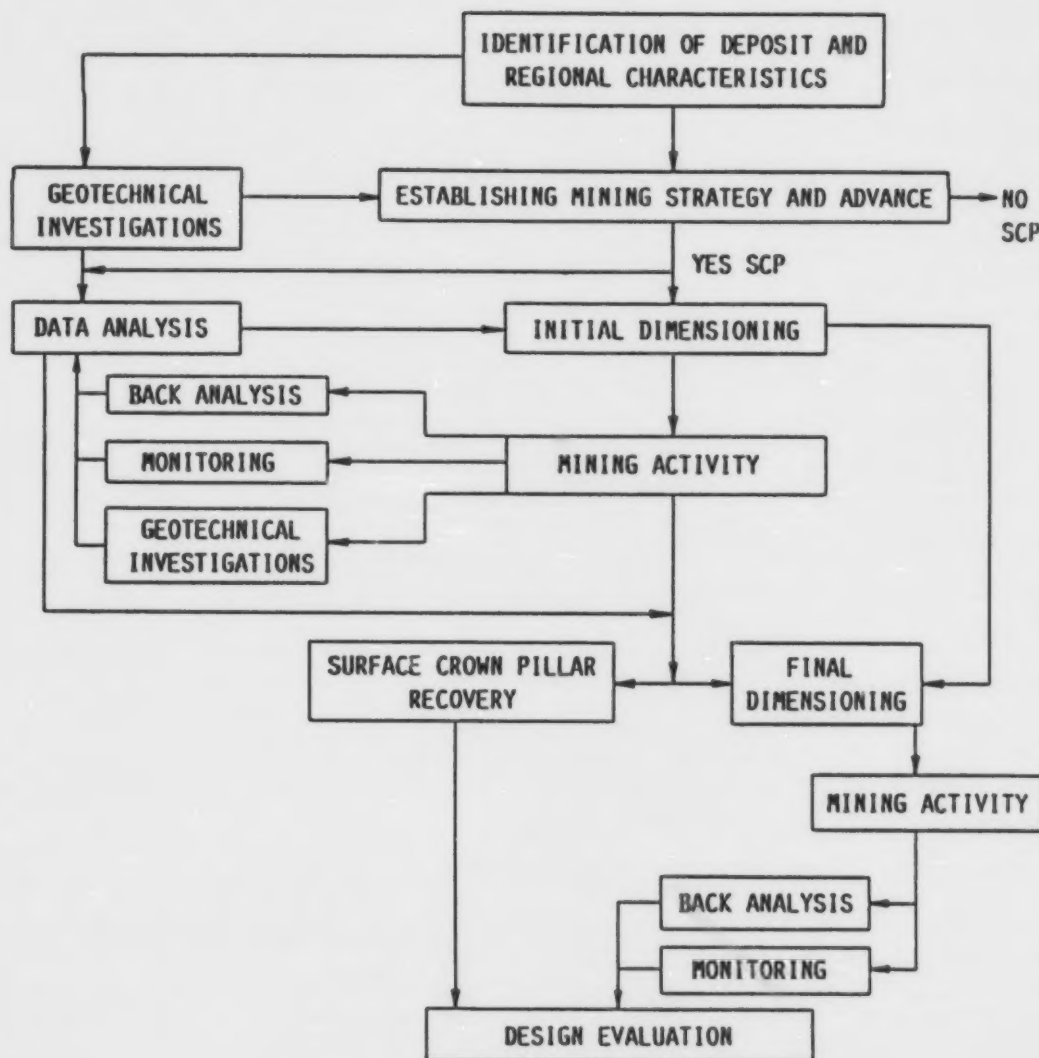


Figure 6.

Design Process for Surface Crown Pillars
(After Bétoumay, 1986, 1989)

5.4 Failure Mechanisms

The concept of failure mechanism as a focal point for the application of design and ground support methods has been emphasized by Bétournay (1989). This concept requires field investigations and material property assessments to be as complete and wide ranging as possible. It challenges designers to apply methods of dimensioning proposed underground openings which can account for all possible failure mechanisms. In order to achieve a proper understanding of failure mechanisms, a number of studies are required of both failures and successes. CANMET is playing a leading role in such studies (Bétournay, 1989), in order to rationalize "experience" and "rules of thumb".

It is possible through proper mapping, classification, in situ testing and analytical/numerical modelling, to assess the probabilities of the various types of failure mechanisms. Such a rational approach to design, aided by field monitoring and model calibration, can substantially advance the cause of economical and safe extraction of ore near or from within surface crown pillars. At Les Mines Selbaie, the concept of failure mechanisms was studied and applied with a great deal of success. A blend of theory and practice was necessary to reduce risks, without adversely affecting production goals. Instead of relying on values of rock mass characteristics derived solely from laboratory tests on samples of questionable representativeness or quality, emphasis was placed on in situ testing and field monitoring, which increased the reliability of computational predictions and enhanced the confidence of the operators in the proposed extractive techniques. Judgement is better made and safely applied when supported by a knowledge of the boundary conditions of a given problem. Parametric studies of the various potential failure mechanisms at Les Mines Selbaie enabled such boundary conditions to be established, making possible a more rational application of judgement and experience.

Elements which are critical to the assessment of stability of openings are existing groundwater conditions, soil and rock properties surrounding the opening, and the volume of rock which may be mobilized by the creation of the opening. The problem is not two dimensional (thickness of rock between soil and top of opening). It is three dimensional. The rock mass influencing pillar stability extends beyond the physical dimensions of the opening, vertically, laterally and longitudinally (Bétournay, 1987).

5.5 Design Methods

Design methods available for the dimensioning of surface crown pillars are (1) empirical, (2) analytical and (3) numerical. Bétournay (1986, 1989) reports that most Canadian mines design crown pillars empirically, with little regard for failure mechanisms. The unusual nature of the surface crown pillar rock mass at Les Mines Selbaie required a "custom-fit" rational approach based on the failure mechanism concept, to achieve stable openings and to ensure economical extraction.

In the first part of the research program, sufficient information was obtained on rock mass and overburden characteristics at the Mine site to suggest that the overlying soil was likely more competent than the surface crown pillar rock mass to provide roof support, subject to the mine being fully depressurized with respect to groundwater. From a geotechnical engineering viewpoint, it was evident that the entire surface crown pillar could be removed safely provided the stope widths were maintained small enough to cause soil arching to occur within the overburden above the opening. It was on the basis of this hypothesis that further research was conducted. Confidence had to be gained in the applicability of the various theories of soil and rock mass behaviour, to ensure that the most likely failure mechanisms were being fully addressed.

Thus, a non-empirical approach was adopted, whereby analytical solutions and numerical models were developed and combined with parametric studies to draw boundary conditions around the problem. This approach gave the Mine operators sufficient confidence to proceed with trial mining. Instrumentation and monitoring of rock mass and soil overburden behaviour during trial mining led to calibration of the models used in the analyses, which in turn resulted in design charts being developed for production mining purposes.

5.5.1 Empirical Methods

The size of underground openings can be estimated on the basis of rock mass classification systems, such as the NGI (Barton et al., 1974) and CSIR (Bieniawski, 1974, 1984). By applying such an approach to the design of surface crown pillars, the span of the pillar can be determined. The safe thickness and opening geometry of the pillar can not be obtained by this approach, however.

In addition, the data used for the development of such classification systems are based mainly on observations which have been made in tunnels. In tunnel design, the ratio of length to width is very large, but in the case of mine openings this ratio may be relatively small. Thus, the design of surface crown pillars based on this approach may be conservative at best, and at worst may be seriously in error. Another empirical approach for the design of surface crown pillars is based on local personal experience. This method may not be totally reliable due to possible variations and alterations in material properties.

5.5.2 Analytical Methods

In this type of method, the pillar is treated as a structural element. With various assumptions, the pillar is simplified and analyzed as an elastic, fixed-end supported beam, an elastic plate, or a masonry arch (Heyman, 1969; Hoek and Brown, 1980).

In the case where the rock mass is altered or fractured, the tensile strength of the rock mass is assumed to be zero and plastic theory can be used to determine the dimensions of the pillar, by treating the pillar shape either as a beam (Pender, 1985) or as an arch (Heyman, 1969). For well-bedded rock masses, design curves for roof and hanging walls based on the Voussoir beam and plate solution developed by Beer and Meek (1982) may be used.

5.5.3 Numerical Methods

Numerical modelling can be classified into two approaches: a continuum approach in which a rock mass is treated as a continuum intersected by a number of discontinuities (Goodman, 1976) or a discontinuum approach (Cundall, 1971) which regards the rock mass as a group of independent blocks. The selection of either approach is based on rock mass characteristics.

Based on a geological description of the rock mass, and from a comparison between the size of the opening and the spacing of discontinuities, a suitable rock mass behaviour model can be selected (Hoek, 1983). With the determination of a rock mass behaviour model, computer codes can be selected or developed for the design of the surface crown pillar.

At Les Mines Selbaie, numerical modelling was used extensively. Parametric studies were conducted for various soil and rock mass characteristics and methods of mining and ore extraction. From such studies, design graphs were generated and used wherever possible.

A large strain finite element code was used in the modelling. First, relatively simple two-dimensional studies were conducted to determine the most likely failure mechanisms. This work was supplemented by base friction modelling. Then, more elaborate three dimensional models were developed for a better assessment of these likely failure mechanisms.

Numerical modelling is described in greater detail in Chapter 8.

6.0 GENERAL EXTRACTION METHODS

This chapter provides an overview of the mining methods considered and adopted at Les Mines Selbaie due to special rock mass and ore body characteristics. Brief descriptions are given of ground control systems used, sizing of stopes, drilling and blasting, backfilling, and dewatering.

6.1 Overview

Exploratory investigations at Les Mines Selbaie were conducted between 1975 and 1978 and included a shaft, cross-cuts, diamond drilling and bulk sampling from the B zone (Bryce, 1990). In 1979 the B zone was put into production. A shaft to the 300 m depth was completed in 1980. The B zone development and construction program took 25 months (Bryce, 1990). Kaolinization and rock alteration is greatest in Stopes 3, 4, 5 and 6, on the hanging wall side of the ore body. Altered rock is mostly concentrated in the bulge of the orebody in the southern part of the B zone, and mining techniques have had to be altered to compensate for the poor quality of rock found here.

An overview and some details of the underground mining techniques employed at the Mine are given by Fourmanoit (1990). In addition to the main 300 m deep shaft, exploitation sub-levels were developed every 20 m, and were linked by a service ramp. The main lens of the B zone extends some 500 m along the strike at the 180 m level, and varies in width between 10 m and 40 m, with a dip angle of 40° to 55°.

Initially, five possible mining methods were considered for ore extraction from the B zone of the Mine. They were:

1. Sub-level retreat
2. Caving
3. Cut and fill
4. Diamond-shaped blasthole
5. Flat back blasthole

The sub-level retreat method was rejected because the dip of the orebody was too flat.

The caving method caused concern with potential induced ground surface subsidence affecting permanent ground surface installations located within 30 m of the ground pillar subcrops. The cut and fill method was attempted but was abandoned due to deteriorating ground conditions during initial mining. The stope backs could not be supported over the full width of the stope. Extensive kaolinization created safety hazards for the steep stope conditions encountered with the diamond-shaped blasthole method (Figure 7a). Since 1983, the flat back blasthole stope method has been adopted (Figure 7b), which eliminates problems with kaolinization and rock mass weakening. It was determined that only 5 per cent of the ore was being left behind. In general, the stopes are set up on 22 m widths (strike direction) with sub-levels every 20 m. A 4 m x 4 m slot (drop) raise is driven down the hanging wall side of the stope by blasting from above. The slot raise is then used as an opening for mass blasting.

Ground control and mine performance monitoring systems, quite apart from those installed for this research project, were established by the Mine. Performance measurements, combined with production records, have resulted in the accumulation of a wealth of useful data, which is faithfully analyzed by Mine staff and management and used for further refinements in design and productivity improvements.

6.2 Ground Control System

Five major programs have been implemented to achieve ground control in the Mine (Bryce, 1985). They are: bolting, backfilling, limitation on stope size, dewatering, and ground monitoring. All developments are rock bolted regardless of rock mass quality. Headings are normally bolted with 1.5 m to 3.5 m long 16 mm diameter Stelco mechanical bolts, depending on rock quality. In the highly fractured or kaolinized ore zones, 1.9 m long Swellex bolts are used at a minimum spacing of 1.2 m. Cement grouted cable bolts (seven strand, 20 mm in diameter) are also used, every second bolt being tensioned. The cable bolts are normally grouted only in their lower half lengths. Cable bolts are employed to hold in place the footwall fault ore, stope backs, and the hanging wall of the stope immediately above the ore being mined. Screens are used in drifts passing through localized weak ground to minimize scaling and to improve mining safety (see Plates XVI and XVII). Load cells, extensometers, ground movement and subsidence measurements and piezometers are some of the monitoring devices in place.

6.3 Limitation of Stope Size

In general, the stopes beneath the surface crown pillar are mined out in 22 m widths along the strike direction. In areas where the orebody is wide (perpendicular to strike direction), and the ground is weak, the stope width is divided into halves along the strike direction. In the weakest ground (and also in the widest and richest part of the pillar), the ore is mined between the 55 m and 70 m levels in 5.5 m wide panels. In better ground, 11 m wide panels are used.

6.4 Drilling and Blasting

160 mm diameter holes are normally used, and are drilled with down-hole drills at the prevailing air pressure of the Mine. In the main lens of the B zone a 4 m by 4 m drilling pattern is used. Explosive charges within the holes are decked (alternate sand and charge). Each deck is ignited separately with two 0.5 kg primers containing blasting caps.

6.5 Backfilling

In the B zone, backfilling serves both as a means of access to the stope above and as ground support (Fourmanoit, 1990). A comprehensive backfilling program is implemented in the mined-out stopes. After mucking, rockfill is dumped into the stope. Usually, the inventory of unfilled stopes does not exceed two months' production. Subsequent to initial rockfilling, fill fences made of timber, screening, burlap and drain pipes are built across the bottom accesses of drifts. Once the fill fence is in place, cemented backfill, consisting of a 1:20 mixture of cement and tailings, is poured into the stope.

The water in the fill is drained off by means of percolation pipes. To ensure safety of the fence, excessive hydrostatic pressures which may develop behind the fence are monitored by means of a pressure gauge. The backfilling operations recommence when the porewater pressure within the backfill has dissipated.

The optimal mix of rockfill and hydraulic fill is 2.2 : 1.0 to achieve the strength required. However, the ratio is closer to 1:1 on some occasions (Caron, 1990, Personal Communication). Usually, 1.5 tonnes of rock backfill is used per tonne of hydraulic backfill, containing cement in the ratio of 1 : 20. The optimum ratio of rock fill to hydraulic fill of 2.5 to 1 has been found to be difficult to achieve (Fourmanoit, 1990).

6.6 Dewatering

Initial groundwater studies for the B zone of Les Mines Selbaie indicated that drilling holes towards the deposit from drainage drifts located in the hanging wall would be the most optimum way of achieving dewatering (Bryce et al., 1983; Bryce, 1985; Fourmanoit, 1990). Drainage drifts were excavated along the hanging wall of the main vein at the 120 and 180 m levels, as illustrated in Figure 8. Some 11,700 drainage holes were drilled in a 40 m x 40 m grid pattern. The groundwater level was lowered to 180 m below the ground surface three years after the implementation of the dewatering program in 1978. Some free water was noted during inspections in 1988 and 1989 at the 55 m level and was thought to be originating within the Mine from drilling activity.

When considering failure mechanisms in the design of safe openings, groundwater plays a crucial role, both in terms of hydrostatic pressures and its influence on geomechanical material properties. In non-cohesive soils, groundwater has little effect on the angle of internal friction between the soil particles, although it will aid in flow type failure mechanisms. In some types of cohesive soils, and under certain conditions of confinement, the presence of free water may lead to loss in shear strength through increased absorption of water into the soil matrix.

Therefore, mine dewatering is an important element in consideration of possible failure mechanisms. The nature and magnitude of failures will depend on hydrostatic pressures, pore water pressures within the soil matrix and the degree of wetting and loss of shear strength of the soil matrix surrounding blocky rock masses. The analyses used should consider carefully the influence of groundwater on the behaviour of soil and rock masses.

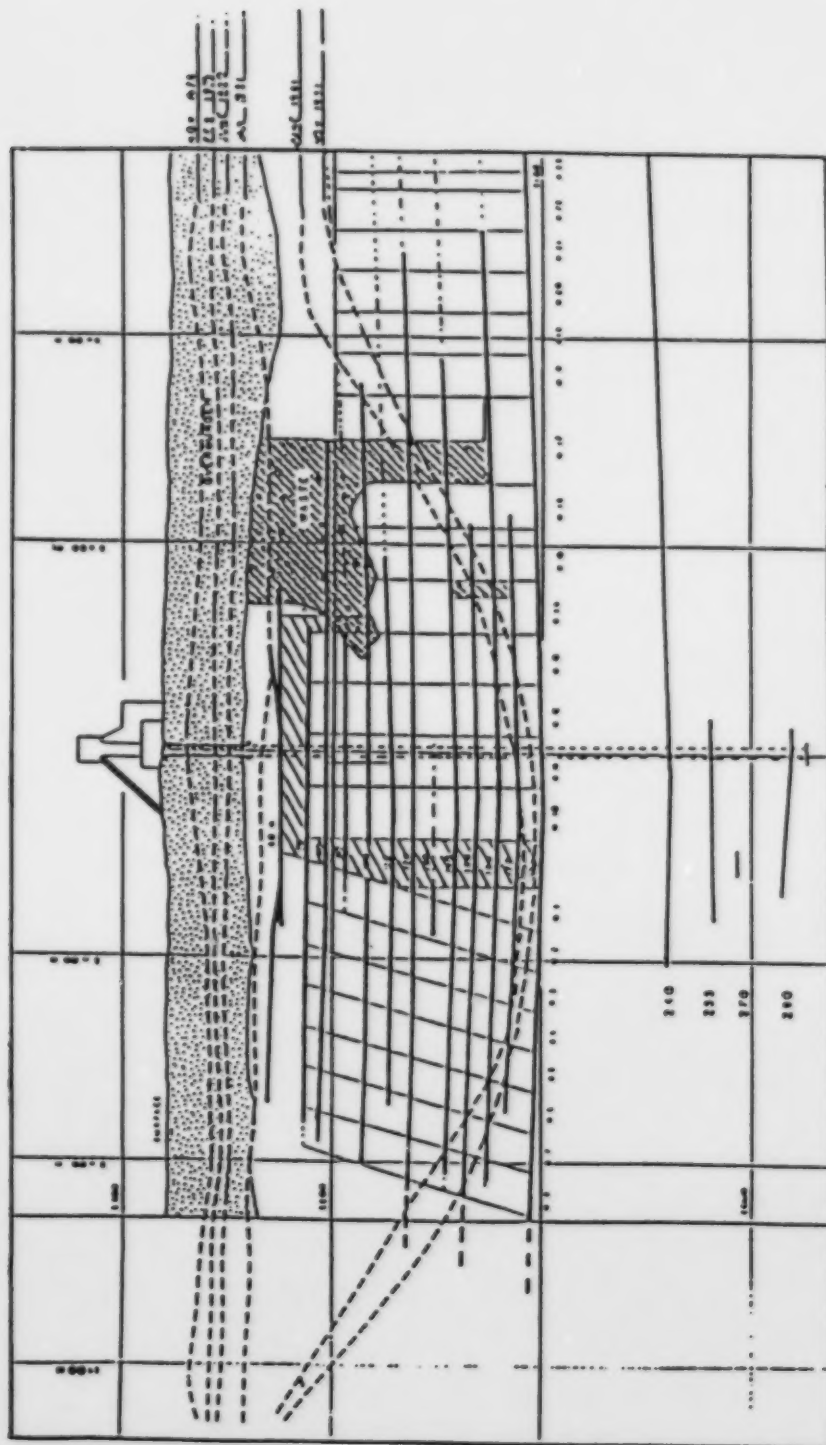


Figure 8. Mine dewatering

7.0 DESIGN METHODS AND BASIC CONCEPTS FOR PILLAR RECOVERY

This Chapter reviews basic concepts associated with failure mechanisms, with emphasis on the behaviour of soils overlying surface crown pillars. The overburden thickness and material properties can significantly influence decisions regarding complete recovery of surface crown pillars without removal of the overlying soil. Failures can range from minor surface settlements or subsidence to cave-ins reaching to the ground surface.

The most probable failure mechanism will depend on a number of factors, including the nature and properties of the soil and rock mass, the shape, size and method of creating the opening, the continuity and contiguity of underground openings, time factors and the degree of ore recovery (ore dilution) desired. Theories of soil and rock arching, granular flow and ground subsidence are described in summary form to indicate the likely failure mechanisms for various types of soil and rock masses, with special reference to the conditions found at Les Mines Selbaie.

7.1 Arching

An underground opening or structure in a uniform soil stratum causes a redistribution of the *in situ* virgin stresses, with consequent deformations. The nature of stress redistribution, the resultant loads applied to the structure, and the support necessary to maintain the opening, are governed by many factors. These include the physical properties of the soil, the geometry of the opening and the stiffness of the structure, as well as static and dynamic surface loadings.

A redistribution of the stresses typically results in a decrease of loading over the opening and an increase in pressure on the adjacent stationary parts. This process of load transfer has been termed "arching" (Terzaghi, 1943; Bulson, 1985). In order for this load transfer to occur, sufficient deflection must occur in the soil mass to mobilize its self shearing resistance.

The pattern of near surface stability, as presented by Terzaghi (1943), can not be used to describe the kinematics of chimney formation. However, the theory can be used to estimate the critical flow initiation state of the material at the onset of flow conditions. Thus, for a prescribed opening width, the limiting values of cohesion can be determined for various shapes of openings (Table 3).

Table 3 Limiting Values of Cohesion for Long and Circular Openings

Width (m)	Type of Opening	
	Long	Circular
3	30 kPa	15 kPa
4	40 kPa	20 kPa
5	50 kPa	25 kPa
6	60 kPa	30 kPa
7	70 kPa	35 kPa
8	80 kPa	40 kPa

Unit Weight of Soil, γ , = 20 kN/m³

A value of cohesion, c' , less than that shown in Table 3 would indicate that gravity induced flow could be initiated. Thus, cohesionless gravels and sands are ideal candidates for flow initiation.

7.2 Surface Subsidence

A comprehensive study of surface subsidence in weak ground due to mining and underground excavations is given by Peck (1969) and Schmidt (1969). These works are supplemented by the works of Peck et al. (1969) and Schmidt et al. (1974).

Underground openings created in soft ground cause changes in states of stress, with corresponding displacements, strains and surface settlements. The magnitude of such surface settlements is markedly dependent on the nature of the ground, including groundwater conditions. In cohesionless soils, the magnitude of the settlements may be negligible if the excavation is well supported. But, if caving and raveling is permitted or desired, substantial settlement may occur and sink holes may develop. The formation of sink holes at the ground surface may be accompanied by a catastrophic flow of soil into the drift heading. Unless the ground is adequately drained, "runs" may develop due to excess hydrostatic pressures. Such running ground can potentially invade underground openings. If the overburden becomes too dry, a tendency for the face to run back towards a loosened "angle of repose" may develop.

While subsidence can not be eliminated, it can be limited by the use of appropriate construction techniques, the design of which must be based on an evaluation of the subsidence problem and on a detailed knowledge of the ground conditions. In general, volume changes which occur due to mining operations are caused by the following factors:

1. Deformations associated with substantial loss of ground at the face due to lack of support, sudden geological changes, or running and flowing ground;
2. Strains and deformations associated with the mobilization of the strength of the soil during the excavation of supporting material at the face of the opening.

The prediction of ground surface settlement above excavations or openings in granular soils is extremely uncertain, because real settlements depend almost exclusively on the details of construction. In cohesive plastic soils, predictions are more rational, provided good supporting data are available for an assessment of the governing soil behaviour parameters.

7.3 Settlement Above Underground Openings

From a variety of case records, it has been observed that surface settlements are more or less symmetrical about the vertical axis of an underground opening, forming a trough-like depression resembling an inverted normal probability distribution curve (Peck, 1969). The geometric properties of the normal probability curve, as used to represent a cross-section through the settlement trough, are shown in Figure 9 in which:

$\delta_{\max}$ = the maximum settlement at any cross section

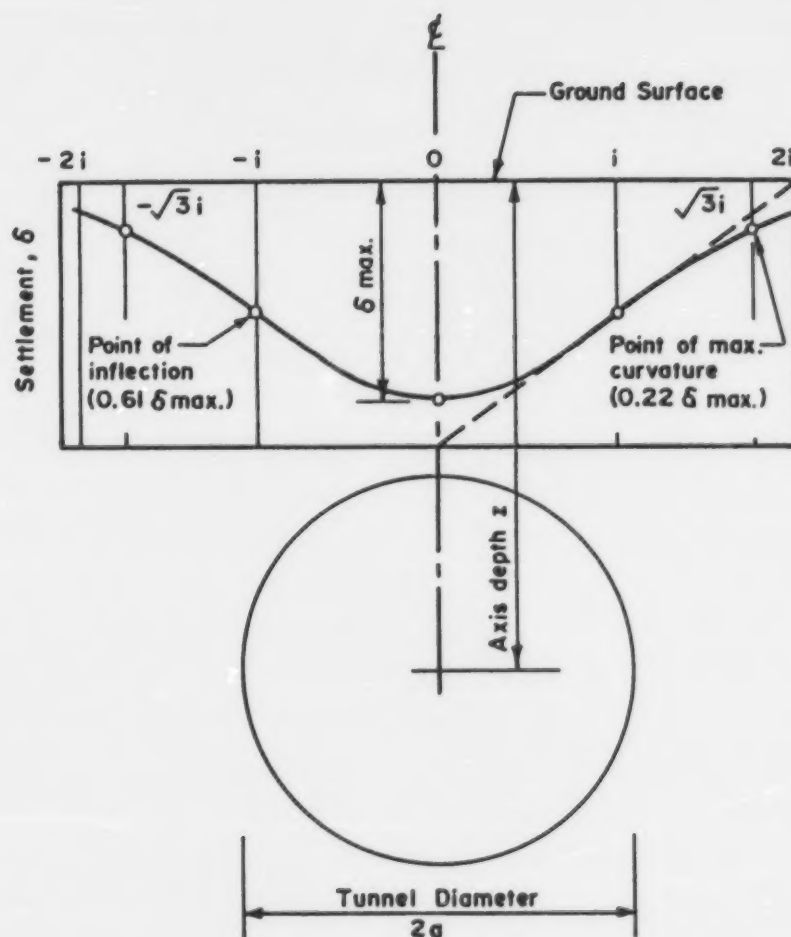
z = depth along vertical axis of opening

a = radius of the underground opening

i = standard deviation of the settlement curve

v = volume of "lost ground" which equals the area of the settlement curve

The parameter, i , is a characteristic distance at which 61% of the maximum displacement occurs.



Ratio $\frac{i}{a}$ is function of $\frac{x}{2a}$ and soil conditions
 Volume of trough $\approx 2.5i \delta_{max.}$

Figure 9.

Normal Probability Curve characteristics

Peck (1969) summarized the results of various observations and measurements related to the deformation and settlement troughs for various tunnel projects. The settlement curve is completely defined by $\delta_{\max}$ and i . The variable i is obtained from equation [1]:

$$i/a = K(z_0/2a)^n \quad [1]$$

which is an empirical derivation based on elastic and stochastic theory and model tests. For granular soils, the value of $K = 1$ and $n = 0.8$. The curve of this equation is given in Figure 10, from which the value of i can be obtained.

$\delta_{\max}$ is then derived from equation [2]:

$$v = i(5/2)\delta_{\max} \quad [2]$$

Thus, estimates can be made of potential vertical ground movements (subsidence) adjacent to various surface structures. The volume of lost ground over a single opening is usually estimated from past experience with similar soils and similar methods of construction.

There is a direct relationship between the volume of lost ground, the size of the underground excavation, the amount of bulking of the material in the vicinity of the excavation, and the volume of the subsidence trough. Thus, the maximum surface subsidence depends on the type and amount of support which is given to the excavation.

The volume of lost ground may range from a few per cent of the excavation volume for a well-supported opening, to that approaching 100 per cent when the ground is allowed to invade the opening, as in a block caving method of mining. Generally, halving the width of a single opening approximately halves the predicted maximum settlement for the same percentage of lost ground with respect to the opening volume. For multiple openings, using superposition, surface displacements are approximately double, and more realistically, due to interaction between excavations, could be considerably greater. The sequence of excavation of multiple parallel drifts for sub-level caving can have a significant influence on the shape of the surface subsidence trough, even though the average surface subsidence may remain the same.

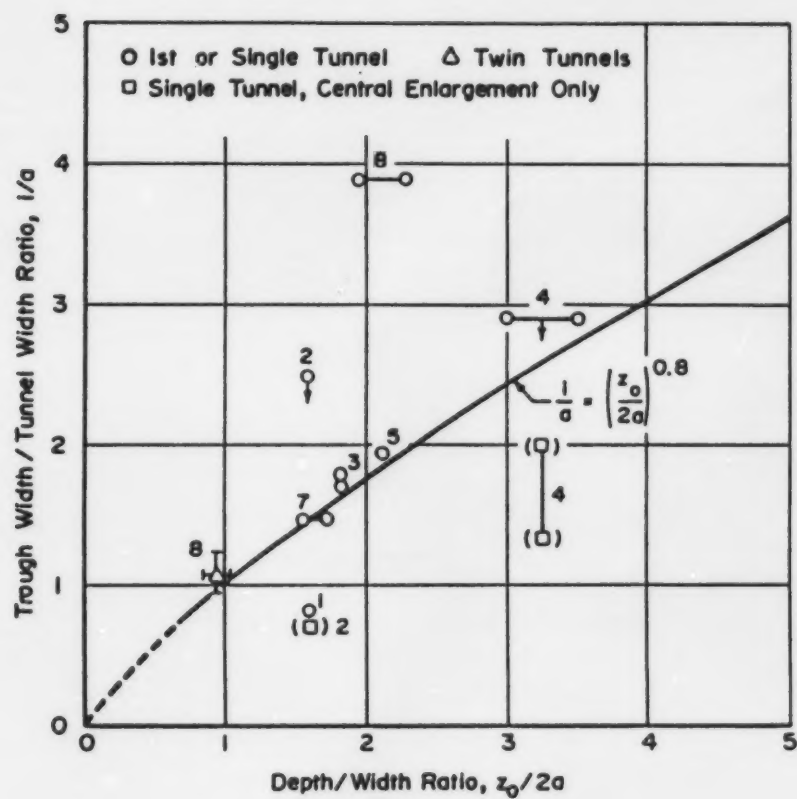


Figure 10.

Subsidence over underground openings in granular soils (after Peck et al., 1969)

7.4 Sub-level Caving and Bulk Flow

Janelid and Kvapil (1966), Yenge (1980, 1981) and Peters (1984) present models describing the gravity flow of ore in sub-level caving mining. The literature on flow behaviour of coarse materials and draw theory is relatively sparse (Peters, 1984). Yenge (1980) discussed the published theories and determined that the work of Janelid and Kvapil (1966) on the "draw ellipsoid flow models" best described the drawing action of columns of coarse materials such as crushed rock in sub-level caving. The gravity flow of coarse aggregates enters the analysis of sub-level caving with respect to the estimate of dilution and ore-loss as well as of potential surface subsidence.

With sub-level caving, the problem of recovery versus dilution and ore loss is potentially very serious (Yenge, 1980), since the extraction of the volume occupied by the broken ore is complicated by the sequential overlapping of the zones of flow of the ellipsoids of motion, and because the ore is surrounded on three sides and above by waste materials.

With sub-level caving, the tonnage draw after blasting a slice is greater than that of the actual ore blasted (Figure 11). During the draw, barren material enters the draw column from above, in front, and from the sides. The draw cut-off limit depends on the ore grade in the slice and the dilution cut-off is often dictated by the processing plant. Excessive dilution and ore loss can be prevented by an efficient draw control and slice design which in turn depends on ground conditions.

7.5 Draw Ellipse Model of Flow

Janelid and Kvapil (1966) developed a gravity flow model which describes the mechanics of flow for both fine and coarse aggregates and which effectively simulates the drawdown of broken rock in underground mining. After blasting a slice in sub-level caving, the broken rock is in a metastable condition. When the bottom outlet is opened, the broken rock begins to "flow" under the influence of gravity.

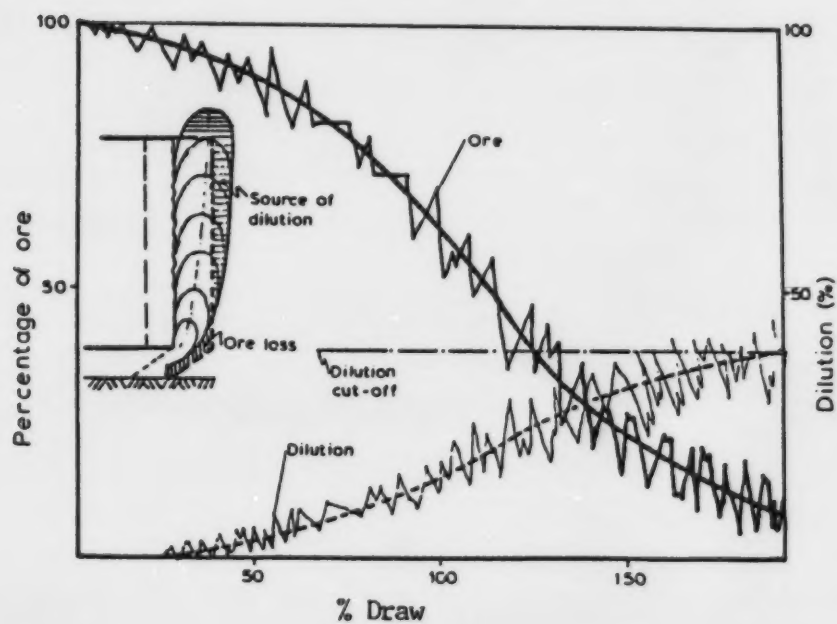
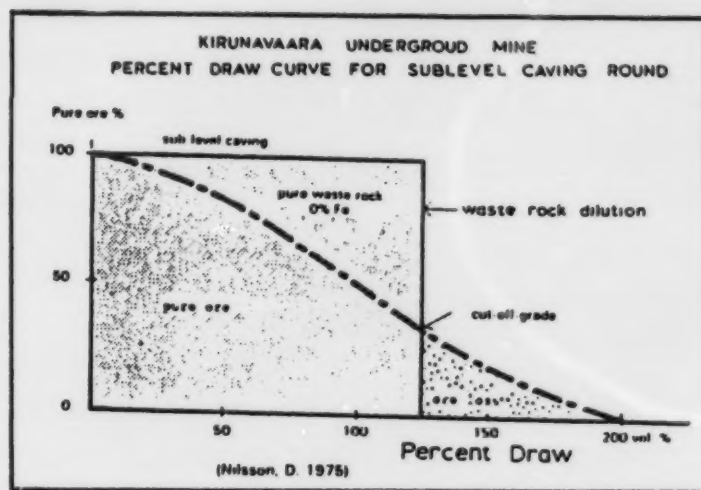


Figure 11. Influence of draw on recovery and dilution
(after Yenge, 1980)

The upward progress of the draw channel is characterized by a systematic formation of a distinct zone with different mobility patterns in order to replace material in underlying regions of lower density with a higher degree of loosening. Figure 12 shows four characteristic flow zones:

- **Ellipsoid of motion:** The region from which all discharged material will have originated;
- **Limit Ellipsoid:** The material between the ellipsoid of motion and the corresponding limit ellipsoid will have been loosened and displaced but will not have reached the discharge point;
- **Draw cone:** The draw cone designates the shortest routes for gravitating materials to reach a draw opening;
- **Dead zone:** The material in this zone remains stationary.

The shape of these ellipsoids is a function of the size of the material comprising the flowing mass, the width of the discharge opening, the spacing of openings, and in situ stress conditions. The height of the ellipsoid of motion and the contained volume is a function of particle size, d_m , Figure 13. The smaller the grain size (or finer the granular material), the slimmer and more elongate the ellipsoid of motion. The influence of the opening dimension on the shape of the flow ellipsoid is shown in Figure 14.

Draw envelopes are influenced by horizontal pressures (Peters, 1984). Pressures applied to only one side may cause a diversion of the draw envelope away from that side. Pressures applied approximately equally to both sides may squeeze the draw envelope and make it thinner. The application of pressure increases the packing of the material on the side nearest the stress, thereby making it harder for the draw envelope to penetrate, diverting the draw into the zone with relatively looser materials. Further details on the governing equations and their use in mining applications can be found in Strata Engineering Corp. (1988) and in Brady and Brown (1985). Figure 15 shows graphically the results of calculations performed for Les Mines Selbaie, assuming multiple parallel drift openings. These show that caving to the surface is likely to occur for such an arrangement of openings for this mine site. Cave-ins at the mine site confirm the validity of this type of analytical approach to prediction of overburden behaviour for sub-level caving mining procedures.

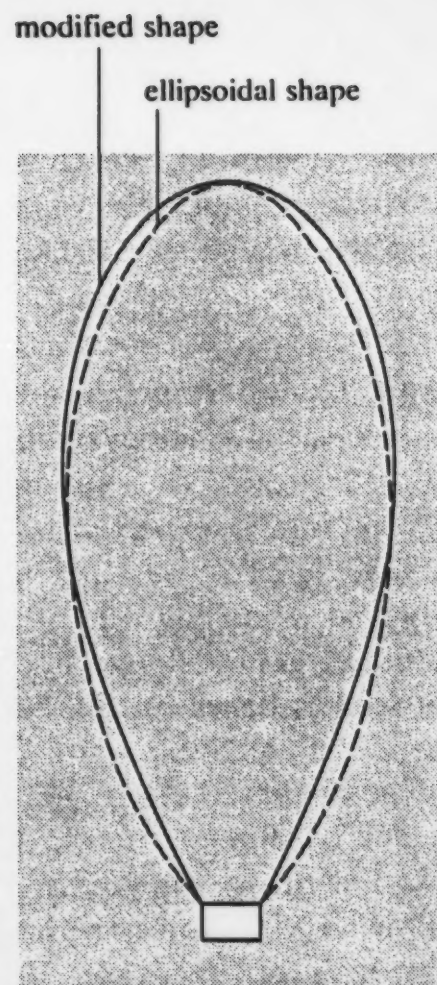
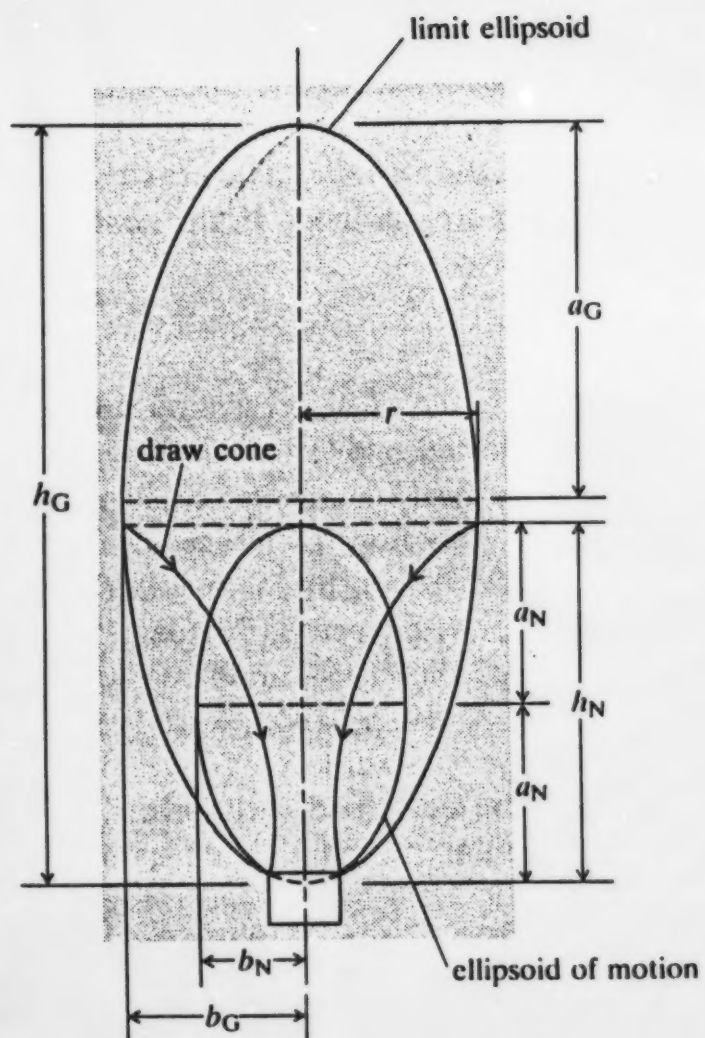


Figure 12.

Flow ellipsoid concept and definitions
(after Janelid and Kvapil, 1966)

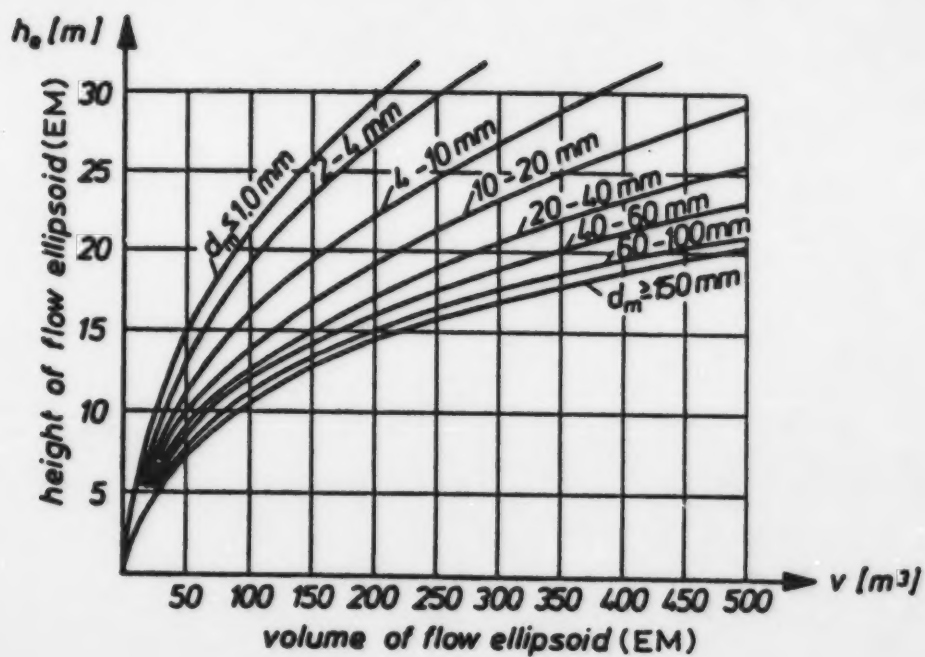


Figure 13.

Influence of particle size on volume of
flow ellipsoid (after Yenge, 1980)

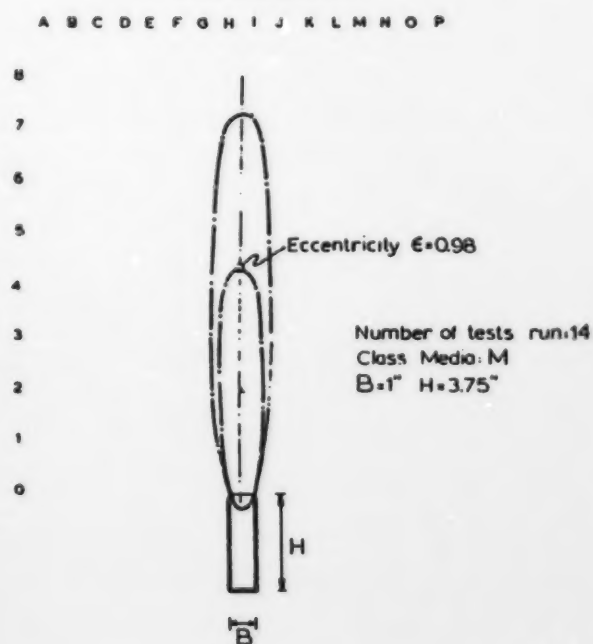
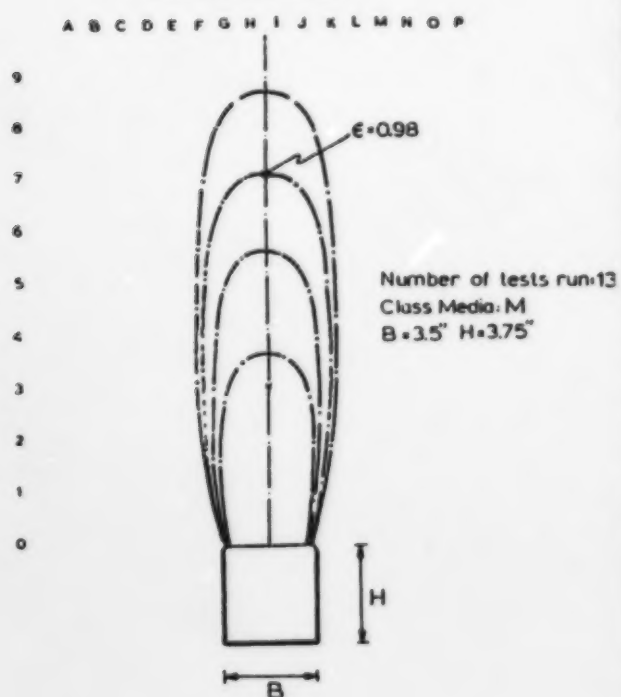
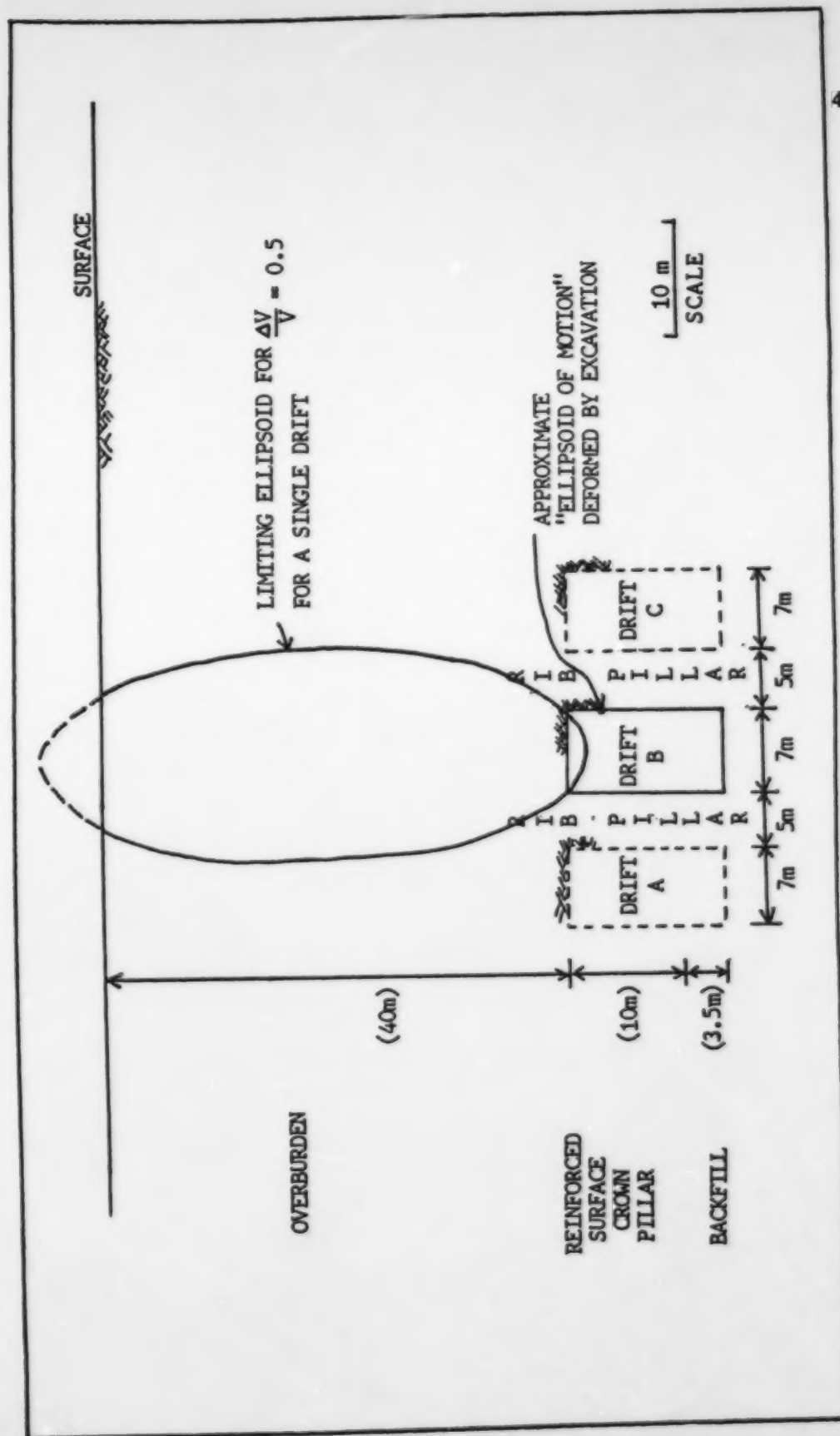
TEST №7-1TEST №7-6

Figure 14.

Influence of Opening size on flow ellipsoid
(after Yenge, 1980)



7.6 Subsidence

Subsidence of the ground surface takes place as sub-level caving proceeds. The overlying material may subside through combinations of continuous and discontinuous processes. The rat hole flow pattern, which is also known as coring, piping or chimney caving, is a condition in which the only active movement is a vertical stream above the discharge opening. Surface subsidence may be discontinuous and of a similar plan, shape and area to the original excavation. The consequence of such discontinuous mining induced subsidence may have disastrous consequences, both in the production part of the mine and through loss of surface installations.

A series of expanding ellipsoids are formed as the fragmented rock in the draw column (within the limit ellipsoid) moves downward (Yenge, 1981). The size of the draw channel depression depends on the particle size distribution of the material, the position and geometry of the discharge opening, and the characteristics of the yielding material in the draw column.

As the drawing of material proceeds, the depression zone progresses upwards until it breaks through the ground surface. The progress of the channel depression due to overlapping effects is typically eccentric. Once an emerging channel depression becomes trapped by an adjacent region of low shear strength material, virtually all subsequent draw columns will divert accordingly.

When the drawpoints are far enough apart such that their draw envelopes do not interact, the results will be the same as for individual drawpoints. Whenever the drawpoints do interact, some modifications occur in the results as compared to individual drawpoints (Peters, 1984). Because the limit ellipsoids are wider than the draw envelopes, they will interact before the draw envelopes do. The overlap of the limit ellipsoids between drawpoints causes a relatively looser zone in that overlap. With the interaction of the draw envelopes, dilution of the ore through overdraw may occur.

Examples of calculations for surface settlements follow.

Example 1 - Calculation of Maximum Surface Settlement Using Peck's Method

Given: Width of Underground Opening = 7 m (= Radius of Opening)

Height of Opening = 13.5 m

Thickness of Overburden = 40 m (above roof of opening)

Solution: $2a = 7 \text{ m}$ Therefore, $a = 3.5 \text{ m}$

$$z = [40 + (13.5)/2] = 47 \text{ m}$$

$$z/2a = 47/7 = 6.7$$

From Fig. 10, for $z/2a = 6.7$, $i/a = 4.6$. Therefore, $i = 4.6 \times 3.5 = 16.0 \text{ m}$

Volume of settlement trough, $\Delta V = i(5/2)\delta_{\max}$. Therefore,

$$\delta_{\max} = \Delta V / (2.5xi) = \Delta V / 40$$

For $\Delta V = 13.5 \times 7.0 = 95 \text{ m}^3/\text{m}$, $\delta_{\max} = 95/40 = 2.5 \text{ m}$

Example 2 - Calculation of Average Surface Settlement

Given: Width and Height of Opening as in Example 1

Length of Opening = 30 m

Rib Pillar Width = 5 m

Solution:

Total theoretical Volume of Material, $V = 13.5 \times 7.0 \times 30 = 2835 \text{ m}^3$

Pitch, $P = 7 \text{ m}$ (width of opening) + 5 m (rib width) = 12 m

Volume of extraction per unit length along strike direction = V/P
 $= 236 \text{ m}^3$

Let: E_n = volume of flow ellipsoid = dimensions of opening = $95 \text{ m}^3/\text{m}$ of drift

E_s = volume of limit ellipsoid = 236 m^3

β = bulking factor = $E_s / (E_n + E_s)$

$E_n = 15E_s = 1400 \text{ m}^3$

Then, $2.5xi\delta_{\max} = (V/P) - (\beta - 1)E_n$ from which (for $i = 20 \text{ m}$)

$$\delta_{\max} = 4.72 - (\beta - 1)28 \text{ in metres.}$$

8.0 APPLICATION OF NUMERICAL MODELLING

This Chapter describes the numerical modelling techniques employed for analysis of stope excavation dimensions proposed by the Mine. In several cases, contingencies of mine planning and production operations resulted in the deployment of opening dimensions and sequence of excavation and backfilling different from those assumed. However, in those cases where the dimensions, methods and sequence of extraction were similar to those assumed in the model, very good correlation was found between predicted and actual behaviour of the stope, surface crown pillar, and the overburden soil.

8.1 General

Numerical modelling is a useful technique to predict material and structural behaviour. For preliminary assessments and parametric evaluations, it is usual to first conduct two dimensional (2D) analyses, since these are faster and take up much less CPU time.

To predict the behaviour of a 7.5 m thick surface crown pillar at Les Mines Selbaie, 2D linear elastic finite element analyses were conducted to predict maximum ground surface settlements near important surface structures, for various sizes of underground openings. The settlements calculated were much smaller than the values predicted from Peck's method. Such small displacements are considered to be the result of the inadequacy of the linear elastic analysis program to model plastic flow phenomena which occur during caving.

8.2 Computer Code Selection

Since plasticity theory has been applied extensively to modelling the behaviour of particulate media (Brady and Brown, 1985), a Mohr-Coulomb type element was used in conjunction with a Lagrangian non-linear large strain finite element analysis for the numerical study of the non-linear responses of the overburden materials. A non-linear large strain finite element code was selected for the study. A multi-dimensional finite element computer code handles rock mass behaviour through its Mohr-Coulomb type elements. The code has a **birth** and **death** option for its elements. This option provides great convenience in modelling, especially for tensile failures. Failed elements can be specified as unborn elements in the next cycle of calculations. Figure 16 shows the flow chart for the computer code.

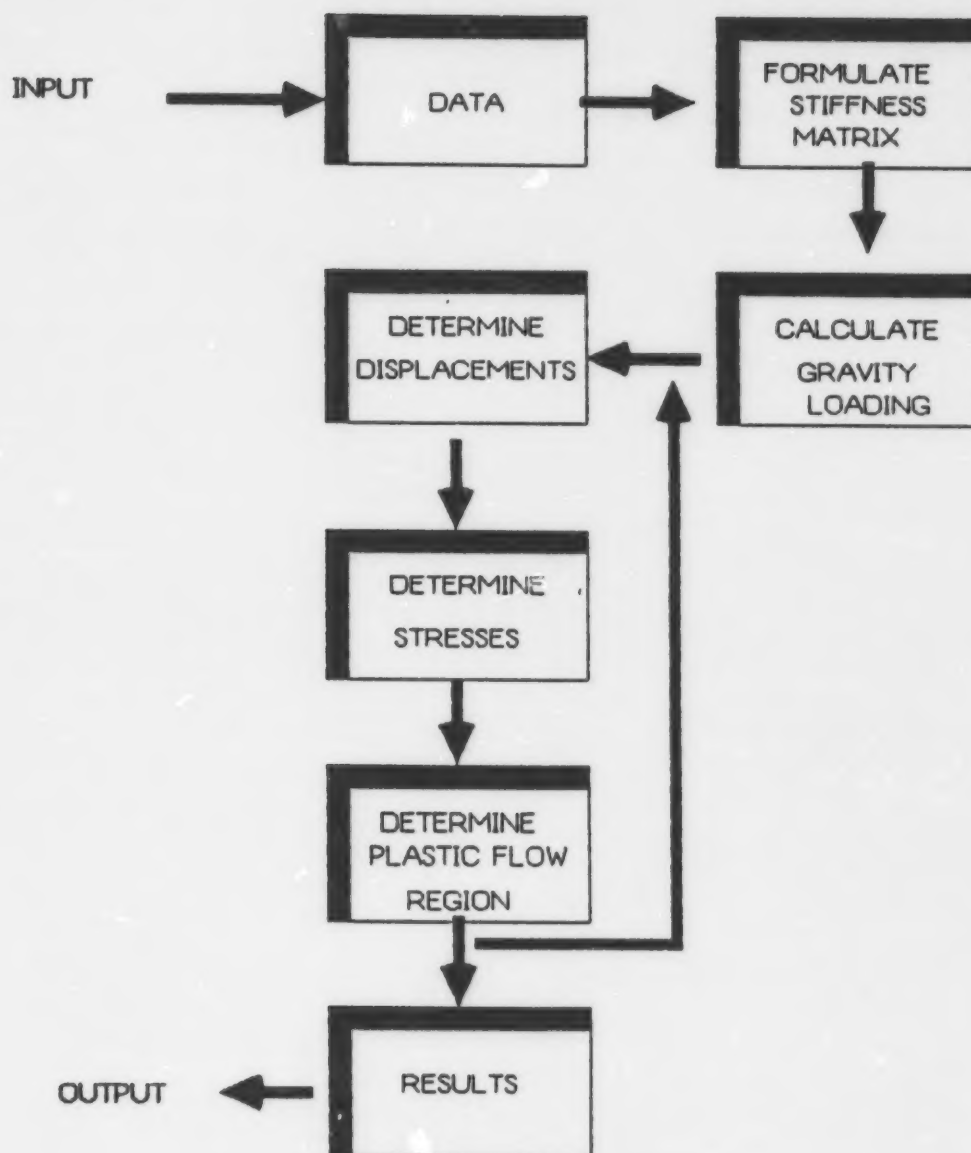


Figure 16.

Computer Code Flow Chart

8.3 Method of Analysis

The underground opening is created by imposing a death option on elements to be excavated. With the application of gravity load, failure in the overburden around the opening occurs. The extent of the failure zone and the settlement of the overburden are outputs from the computer program. With the determination of the extent of the failure zone, those elements lying within the zone are then eliminated by use of the death option. The intent of removing these elements is to ensure that when the failure zone becomes kinematically unstable, it will flow into the excavation. When such motion occurs, the failure zone detaches from the overburden.

Through such an elimination process, the extent of progressive caving of the overburden can be determined. With progressive overburden caving, the channel depression zone progresses upwards until it breaks through the ground surface. Once the channel depression reaches the ground surface, surface materials slough off the sides of the crater to refill the cave. When this situation occurs, the numerical model becomes unstable. The analysis provides the extent of the caving region and displacement in the overburden before the occurrence of channel depression break-through.

Thus, a method for the determination of the final ground surface subsidence can be formulated. For a 2D case, the mesh employed in the modelling is shown in Figure 17. Five hundred and six (506) four-node quadrilateral elements were implemented in the analysis. The analysis consisted of an overburden thickness of 40 m with an opening 7 m wide and 13.5 m high. The overburden material was assigned a friction angle, $\phi' = 35^\circ$ and a cohesion intercept, $c' = 17$ kPa.

The dimensionless settlement curves at the ground surface predicted by the analysis are plotted in Figure 18, with Peck's probability curve superimposed for comparison. The results show that with the consideration and determination of the bulking effect, the model can be used to predict ground surface settlement before instability occurs. The results also indicate that the final ground surface subsidence can be determined by the method proposed by Peck. It should be noted that the subsidence profile has a characteristic length "i" of 16 m, comparable to the value obtained from Peck's empirical data. Such a correspondence emphasizes the usefulness of Peck's data in calibrating the numerical model.

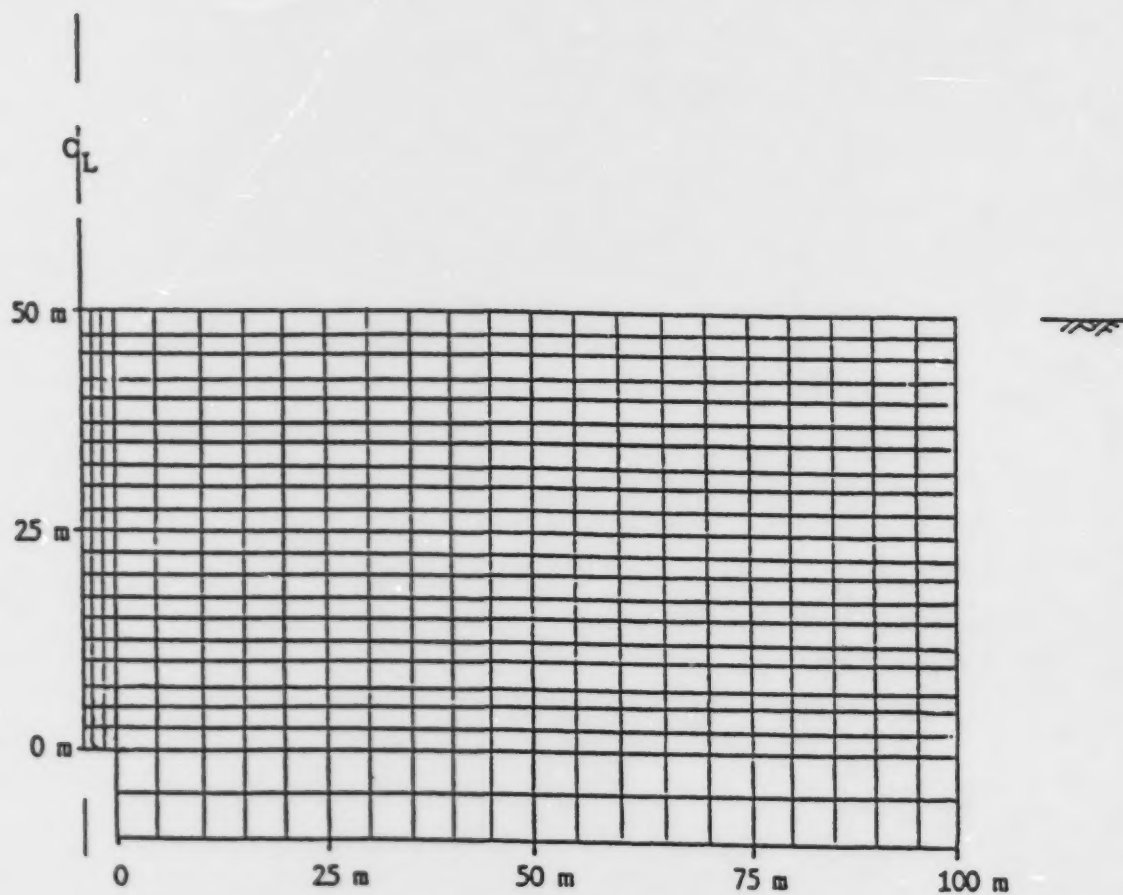


Figure 17.

2D finite element mesh used in numerical modelling

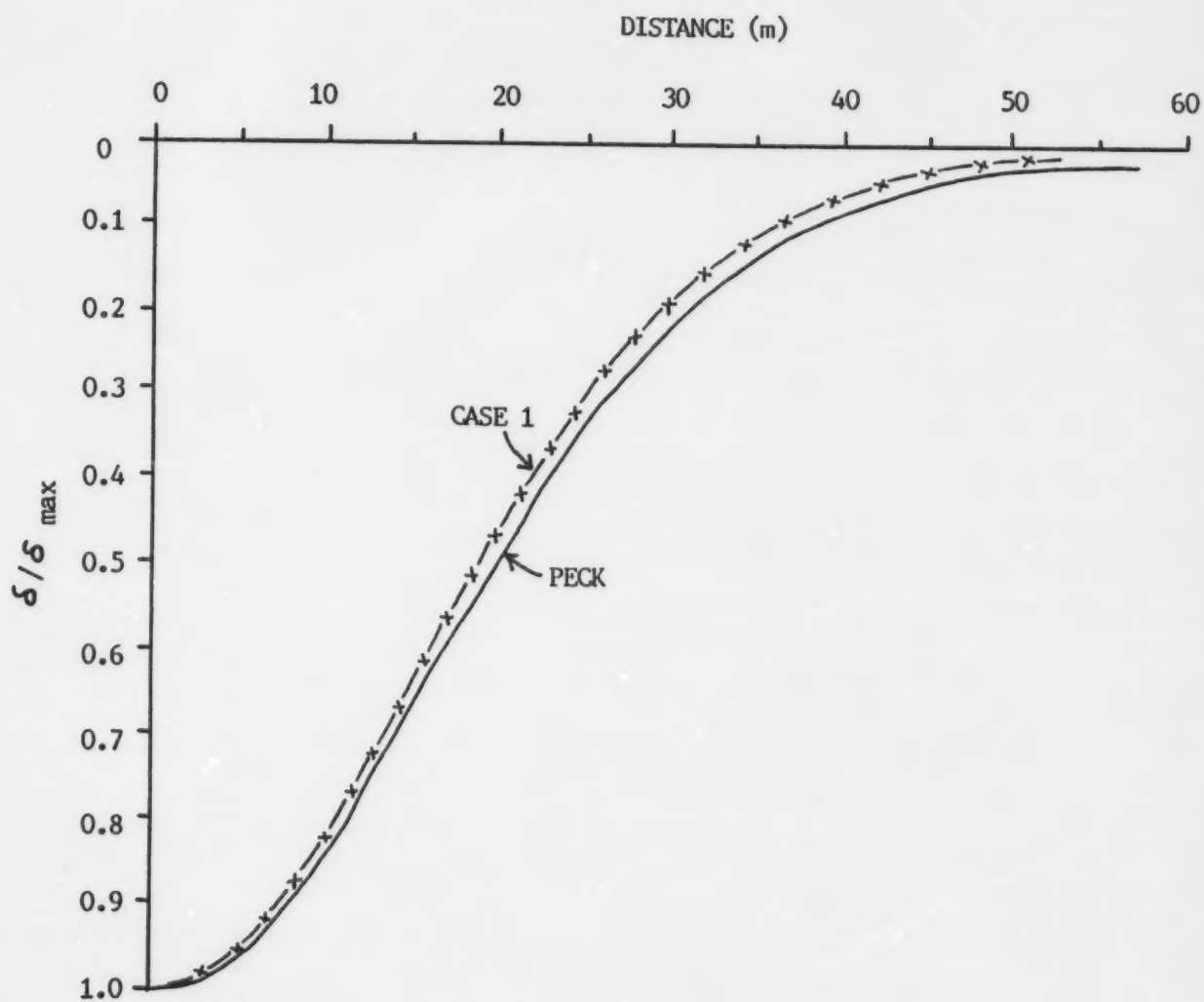


Figure 18.

Comparison of numerical modelling results
with Peck's theory

8.4 Model Validation

With the selection of the Mohr-Coulomb failure criteria as the physical model for the overburden materials, numerical analyses were conducted to validate the model.

The model for the analyses consisted of an overburden 40 m in thickness with openings 3.5 m and 7.0 m in width by 13.5 m in height. The vertical displacement due to progressive caving for a 7.0 m wide by 13.5 m high opening, at different elevations of the overburden, is shown in Figure 19. The formation of a limit ellipsoid is clearly apparent.

With the preliminary calibration of the numerical model incorporating the associated Mohr-Coulomb elements, both 2D parametric and 3D specific studies (see Figure 20 for the mesh used in the 3D analysis) were conducted to determine the significance of the various parameters to the caving phenomena. The analyses indicated that for the range of soil properties studied, the effect on the characteristics of ground subsidence were minimal. In the prediction of magnitude of ground subsidence, the bulking factor was the most significant parameter. The validity of this approach, if breakthrough occurs, was proven in Phase IV of this research study (Strata Engineering Corp., 1990).

The effect of multiple openings on the characteristics of the ground surface subsidence were investigated. Dimensionless settlement curves for both the numerical study and Peck's data are plotted in Figure 21. The curve for Peck's data was obtained by superposition. The similarity of these two curves indicates the validity of applying the principle of superposition for the prediction of ground surface subsidence.

Cave "A" (see Section 9.3, this report) which occurred at the Mine site in 1983 was used to calibrate a 3D finite element model, as illustrated in Figure 22a. A comparison of predicted versus actual failure of the cave along the strike (Figure 22b) and normal to the strike (Figure 22c) shows excellent correspondence between theory and observations (Strata Engineering Corp., 1987). Figure 22d shows design charts prepared specifically for the Mine. Knowing the orebody thickness, L (along the x-axis), at any given location, and after assessing the rank of the rock mass according to the Quick Field Classification developed for this site, the designer can select a safe mining panel width, W , for recovery of ore from the surface crown pillar.

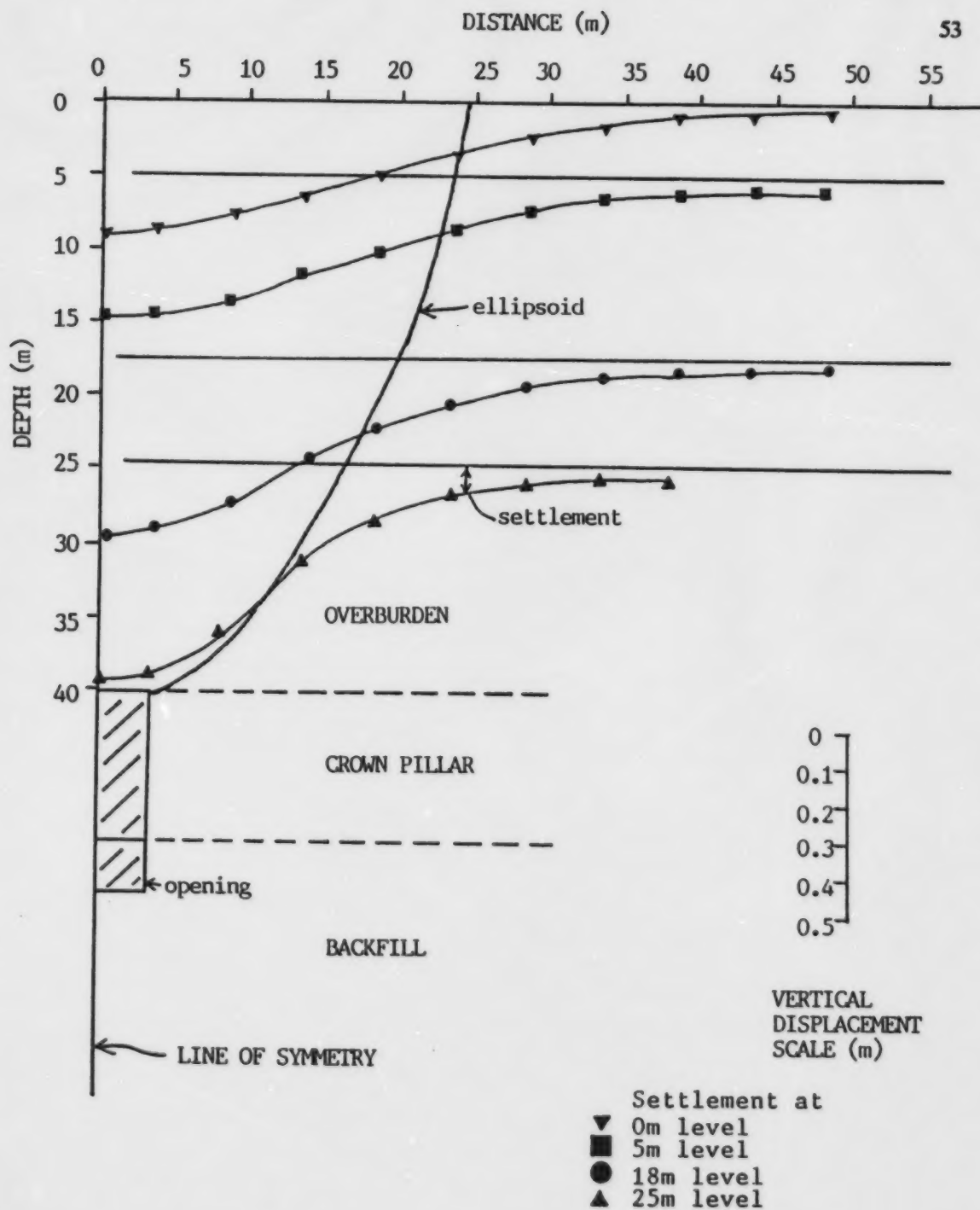


Figure 19.

Predicted vertical displacement above stope for 7m wide opening

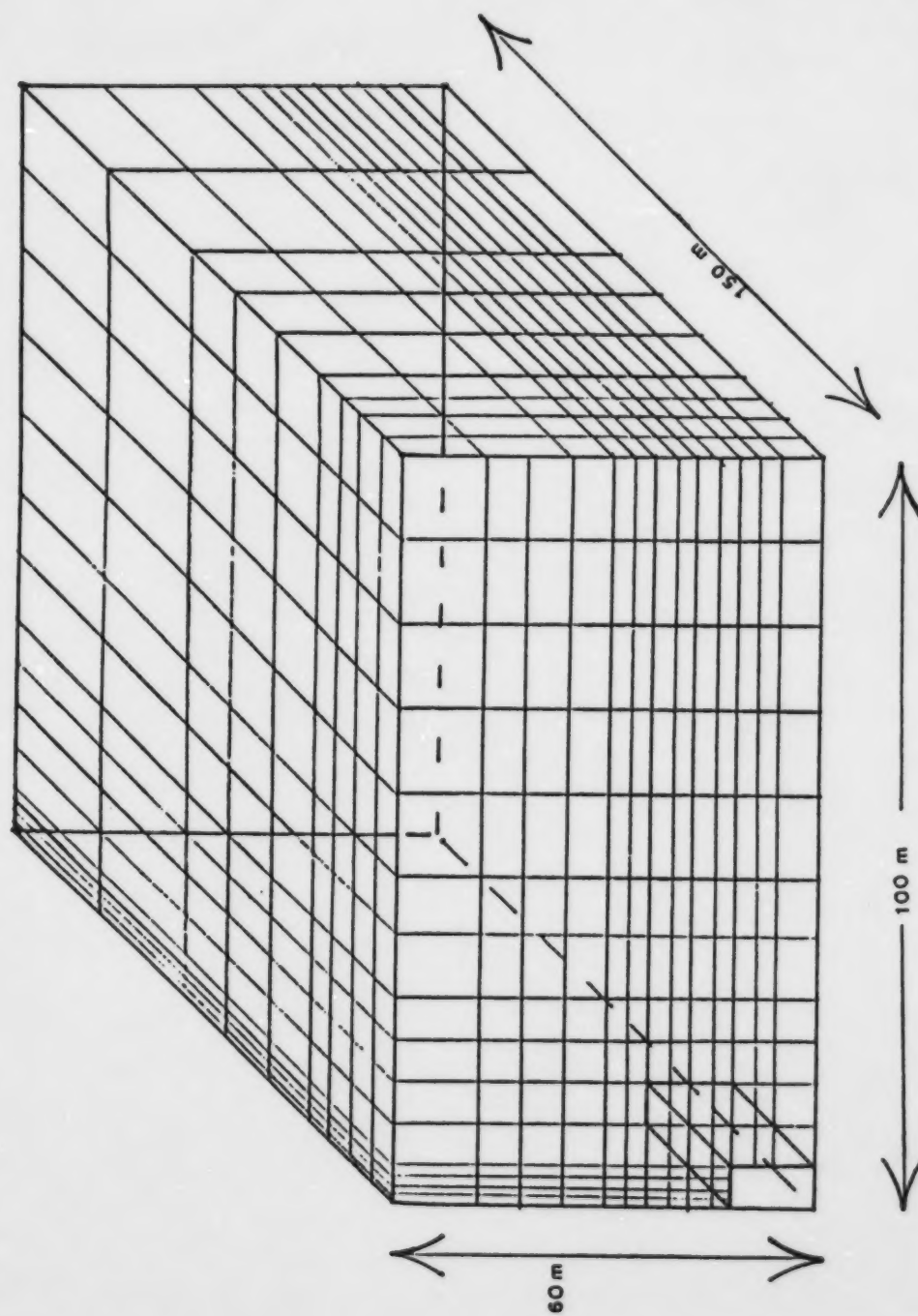


Figure 20. 3D finite element mesh used in numerical modelling

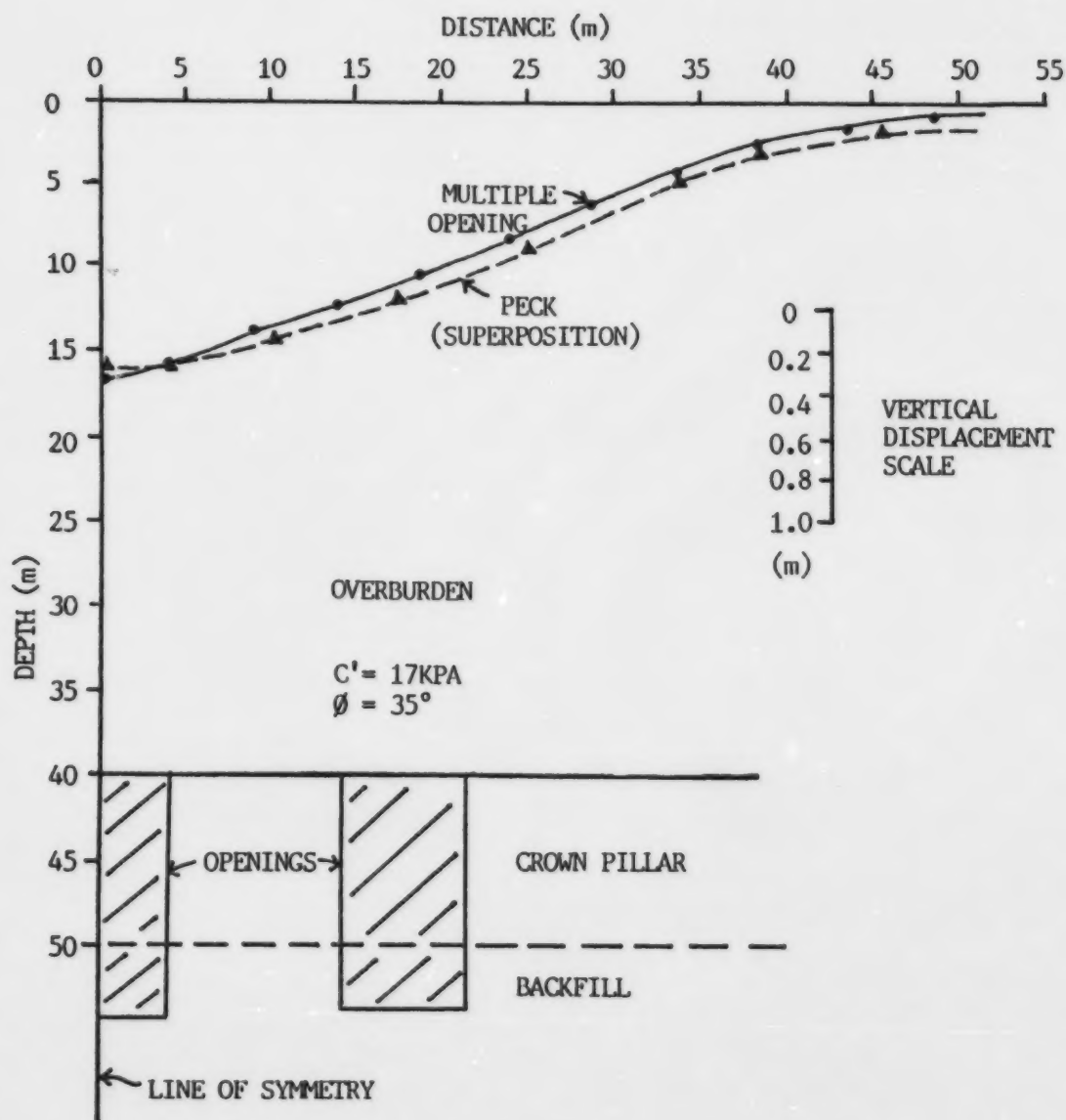


Figure 21.

Ground subsidence over multiple stopes

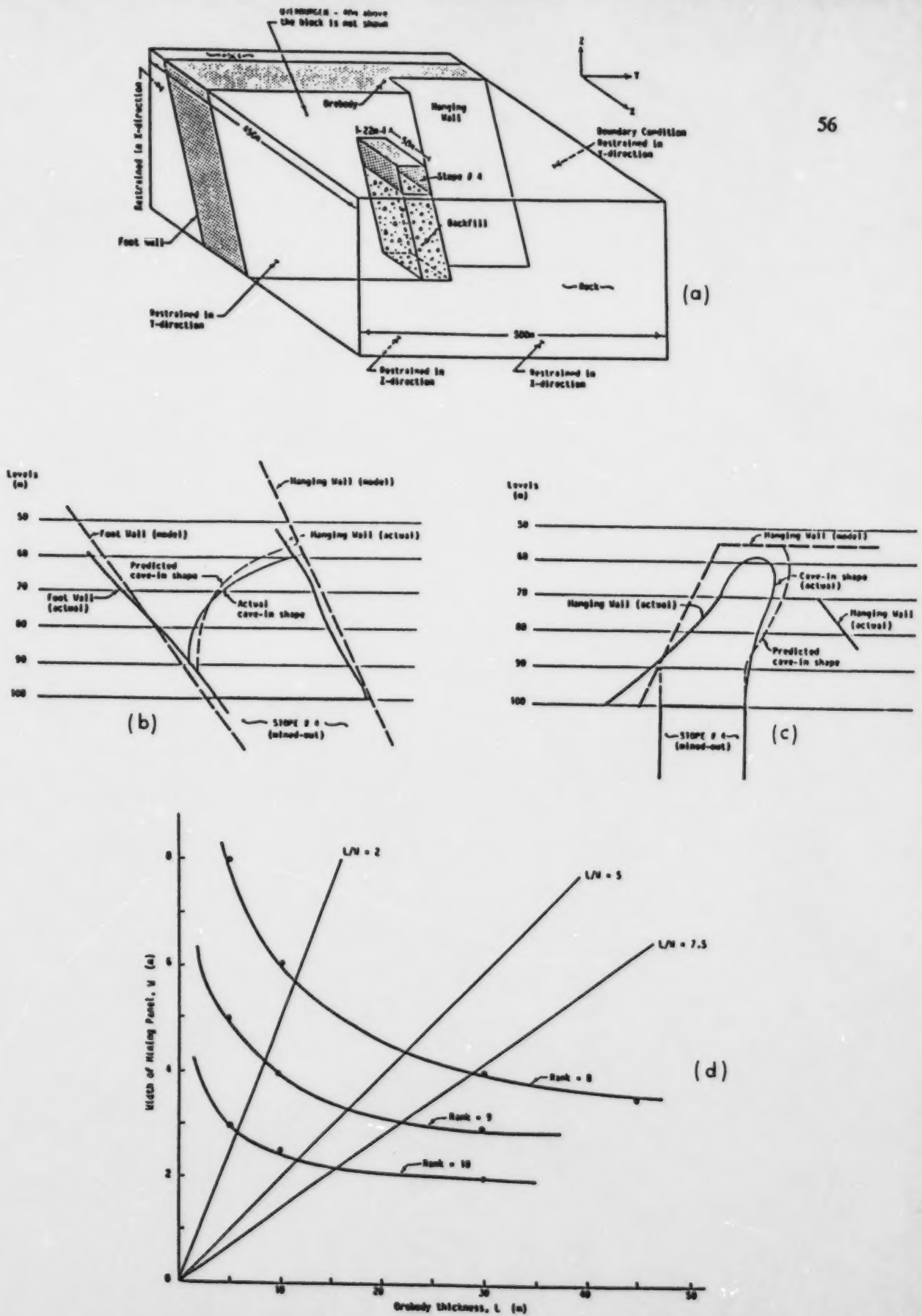


Figure 22.

Model validation (a, b, c) and design chart (d)

From these analytical and both 2D and 3D FEM modelling studies, and by comparisons with data obtained from field studies, the following observations are pertinent:

- analytical models can be used to predict the extent of the failure zone;
- analytical models can be used to predict the subsidence profile above openings when breakthrough to the surface does not occur;
- the analytical model used in this study has been validated with data from laboratory model tests and field data compiled by Peck;
- in case of surface breakthrough, surface settlement can be predicted by Peck's method, paying due consideration to material bulking properties;
- the most important parameter in the determination of surface settlement is the bulking factor, β .

In the case of recovery of ore in the surface crown pillar by the control caving method, the bulking factor, β , determined by actual field trials at Les Mines Selbaie, was found to be 1.15 (Strata Engineering Corp. 1990). Therefore, the ore dilution due to inflow of overburden materials upon draw of ore is expected to be less than 50 per cent, and this was found to be the case by the Mine (see also Chapter 9).

9.0 ORE RECOVERY

This Chapter discusses methods by which the Mine effected ore recovery. Results of the economic analyses conducted by the Mine are also given. Much of the information given in this Chapter was provided by Les Mines Selbaie. A full economic report on ore recoveries and profits may be found in Les Mines Selbaie (1989).

Also included in this Chapter is a history and documentation of cave-ins which have occurred at the Mine site. The data has been provided by the Mine (Caron, Personal Communication, 1990). Data for Caves A to C are taken from Jolink (1985).

9.1 Methods of Ore Extraction

Ore recovery was to be effected through 7.0 m or 3.5 m wide by 13.5 m high drifts from the footwall, with 5 m wide rib pillars left in previously placed backfill located immediately beneath the surface crown pillar. However, this plan was modified due to ground conditions.

The major method of mining of the surface crown pillars at Les Mines Selbaie has been slot raise and bulk mining. This is a departure from control caving by slashing which was originally planned. The change was necessary in the interest of safety, and the decision not to recover completely any ore located above the rib pillars. In part, this decision was forced by concerns with the poor quality of the ore rock and the proximity of some structural facilities above ground in areas expected to be prone to future cave-ins.

In the surface crown pillar zone, the orebody thickness ranges between 4m and 30m (footwall to hanging wall), dipping at approximately 60°, and oriented north-south. Where the orebody thickness is narrow (<10m), Stopes 02, 10 and a part of 13 were mined out longitudinally. In thicker areas, mining was done transversely.

Slot raises were 2 m by 2 m in size and were planned to be mined in one blast, after drilling 5 m to 10 m. Between 25 and 30 holes were drilled in each slot raise. Slot raises in some cases had to be blasted twice, if the first blast did not succeed in reaching to the top of the raise. In better rock conditions (eg. Stopes 10 and 11), the slot raise was blasted in a retreating manner, blasting three or four rows per shot.

ANFO is used for blasting. Fully loaded drill holes are common practice. Central holes are blasted first, followed by the side holes. Collar size is generally 500 mm. In wet conditions, a water resistant explosive is used. Ignition is with nonel delay. Each nonel (one per hole) is connected to a trunkline. Microconnectors are used for the required timing. The Mine tried not to shoot more than 120 kg per delay, and discovered that in some cases less would have been better.

In general, slot tonnages ranged between 70 and 120 tonnes. Total ore yields per stope ranged between 3 and 7 tonnes per meter of drilling and blasting.

The size of openings varied in width between 5 m and 10 m and in height between 10 m and 15 m (including undercuts), and in length from 8 m to 15 m. The development in the orebody was accomplished with a jumbo. The undercut was maintained at a minimum height of 3.5 m.

Mucking was done with scoop trams. Remote control scoop trams were used inside stopes. In the southern part, an undercut was not necessary. The overcut resulting from the drilling and blasting of the crown pillar between the 55 and 70 m levels was used as the undercut to recover the surface crown pillar. Overcuts were all previously backfilled with rock and hydraulic fill, which had to be removed for the undercut. Generally, a thin remnant crown pillar of 1 m to 2 m thickness was left in contact with the overburden to prevent caving. This succeeded only on a few occasions.

It took an average of 10 calendar days from the time of initial slot raise to final documentation of the shape of the stope roof. This includes about 1 day to load and blast and 2 days to muck out the stope. At all times, ground controls were fully in effect to ensure safety of workers.

The shape of the final roof is determined by surveying from two laser stations. The survey data is reduced and plotted by a computer program, designed and implemented by the Mine.

In good quality materials, ore recoveries were generally in excess of 75 to 85 per cent of the planned or estimated tonnages. In poorer rocks, due to steeper arching, ore recoveries were generally in the order of 10 to 40 per cent.

9.2 Tonnages and Grade

9.2.1 Reserves and Estimates

It is estimated that within the remnant pillar (7 to 10 m thickness) some 69,500 tonnes of ore was available. The Mine expected recoveries of about 40 % (at a 25 % dilution) for the north side (Stopes 03 to 07) and 45 % (at a dilution of 10 %) for the south side (Stopes 11 to 13). This indicated total minable reserves of slightly over 36,000 tonnes, with an average NSR (Net Smelter Return) value of \$72.71 per tonne. The ore grades after dilution for this tonnage were 1.80 g/t gold, 32.1 g/t silver, 3.49 % copper, and 0.6 % zinc. The theoretical total revenue expected from this minable reserve was \$ 2,630,198. Assuming an average cost of production of \$50/tonne, the profit expected was about \$822,998.

Metal prices (Canadian \$) used in the analyses were:

Gold	\$460/oz
Silver	\$9.56/oz
Copper	\$0.97/lb.

For stopes 10-13 in the north part, some development of the ore using Jumbos was required, including an access ramp in the waste. For Stopes 03 to 07, development was complete and no extra costs were anticipated.

Developmental costs for the north part were computed as follows:

Development for access (ramp in waste)	\$ 7.11/t	
Development in orebody	\$ 5.68/t	
Production costs, incl. b/fill.	\$25.58/t	
Concentrator costs	\$ 6.76/t	
Administrative costs	\$ 5.32/t	
Plant (overhead) costs	\$ 5.32/t	Total \$57.90/tonne

For the south part, the cost was $\$57.90 - \$7.11 - \$5.68 = \$45.11/\text{tonne}$.

9.2.2 Actual Tonnages and Grades

Table 4 shows the tonnages recovered from the surface crown pillars at Les Mines Selbaie.

Table 4 Recovery of Ore from Surface Crown Pillar

Stope No.	Geological Reserve (t)	Ore Reserve (t)	Actual Blasted Tonnage (t)		Mucked Tonnage (t)	
5-1-02	4972	2486	4087	4087	1944	
5-1-03	5539	2769	812	812	914	
5-1-04	6427	3213	2488	2488	828	
5-2-11	4000	2000	3076	3076	5012	note 1
5-2-12	11282	5641	-	-	1349	note 2
5-2-13	7393	3696	1504	1504	3296	note 3
Subtotal	39613	19805	11967	11967	13343	
5-1-05	13217	6608	not mined			
5-1-06	17591	8795	not mined			
Subtotal	30808	15403				
Total	70421	35208	11967	11967	13343	
5-1-07ABCD	20400	not included under minable reserve				note 4
5-1-08	13144	not included under minable reserve				note 4

NOTES

1. Developmental tonnage was 1686 tonnes
2. Slashing tonnage was 1349 tonnes
3. Includes development of 1549 tonnes.
4. Not recovered (reserves lie below built up areas)

From the north part (Stopes 11 to 13) 9,657 tonnes were mucked out of a minable reserve of 13,800 tonnes. Some rib pillars were left in place in Stope 13 after a cave-in occurred following blasting in Stope 5-B-13. In Stope 5-2-12, only some slash development occurred so this part was also not fully mined out, due to concerns over surface facilities (conveyor supports).

The actual grades after dilution for the 9,657 tonnes mucked out were:

Gold	1.68g/t
Silver	35.12g/t
Copper	3.56%
Zinc	0.89%

with an NSR value of about \$72.58/tonne.

This resulted in a net profit of $9,657 \times (72.58 - 57.90) = \$141,789$.

In the south part, only 3686 tonnes was mucked out of a minable reserve of 23,000 tonnes. The Mine encountered not only very much poorer rock quality but also some groundwater problems. Stopes 5 and 6 were virtually unmined due to prior caves between the 70-80 m to 55 m levels. In stope 4, a cave in the first trench inside the remnant pillar prevented further extraction. In Stopes 02 and 03, the rock quality was considered very poor and thus not minable.

The actual grades after dilution for the 3,686 tonnes mucked out were:

Gold	1.65g/t
Silver	32.61g/t
Copper	3.14%
Zinc	0.36%

with an NSR value of about \$66.72/tonne.

This resulted in a net profit of $3,686 \times (66.72 - 45.11) = \$ 79,671$

Hence, the total profit realized was $\$141,789 + \$ 79,671 = \$ 221,460$.

The total profit realized was much less than originally planned, partly due to mining difficulties and partly owing to safety considerations (presence of water being detected in the south part).

9.3 Cave-in History

Complete recovery of surface crown pillars could result in either unacceptable ground settlements (with consequent influence on surface structures) or in cave-ins which may manifest as open or closed depressions at the ground surface. This research has examined several analytical methods by which cave-ins and ground subsidence may be predicted. A history of cave-ins at the Mine is therefore provided here as a matter of record.

Cave "A" - Fall 1983

This cave occurred in Stope No.4. The material involved was about 10,000 tonnes. The cave started at the 100 m level and progressed upwards to approximately the 60 m level, over a duration of 6 to 8 months. At the time of the cave-in, the ore was being mined with the diamond-shaped blasthole method. After the initial stope was blasted, the lower half of the diamond began to scale, creating unsafe working conditions. This piece was then blasted, leaving a flat back stope with a span of approximately 55 m across the strike of the orebody.

Cave "B" - Summer, 1984

The second cave occurred in stope 05. The stope was being mined to the 80 m level. Blasting of the ore up to that level caused the rock to cave-in up to the 70 m level.

Cave "C" - January 1985

A third cave-in occurred, with a suspected volume of 10,000 tonnes (quantity estimated from backfill used). At the time of the cave-in mining was being done between the 160 and 140 m levels. The rock above the open stope, mixed with backfill from adjoining stope 2, caved in to the 120 m level. After mucking (the ore and backfill mixture was sent for processing), another slash was blasted, and once again the back of the stope caved up to the 120 m level. When this material was mucked, the cave progressed to the 100 m level, blocking off access at the 120 m level, and leaving large open fractures at the 100 m level.

Cave 05-C-08 - November 1985

The back of stope 08-C-08 failed on the footwall fault after the stope was blasted. The cave did not reach the overburden. It is suspected the cave was caused by an unsupported 6 m by 6 m back and blasting of a sub-drilled post-pillar. The pillar was removed and the stope was sealed, using a few more cables than normal.

Cave 05-BC-06 - July 25, 1986

This cave reached the surface. The back failed while developing the southeast fault. A hole drilled in May 1986 is felt to have caused instability in the surrounding overburden, since the chimney followed the hole to the surface.

Cave 05-2-13 - March 8, 1988

The cave-in started on March 8, 1988, and progressively arched to the surface on March 17, 1988. This stope was designed to cave the surface crown pillar. The caving followed the predictive model very closely. A minor variation near the ground surface is attributed to frozen ground which resulted in a deviation of the chimney path near the surface.

Cave 05-D-05 - May 30, 1988

After blasting stope 08-D-05, the overburden collapsed instantly. The failure is attributed to insufficient pillar thickness between adjoining stopes.

Cave 05-2-10 - June 1988

While mining the remnant pillar, the overburden was exposed on a section measuring 3 m by 4 m, which did not cave for more than 21 days. It was decided to increase the stope dimensions after this experience with the stability of the overburden.

Cave 05-2-11 - August 1988

The overburden was exposed on a section measuring 3 m by 6 m and did not cave for about two weeks. It then began to arch with an estimated 50 tonnes coming down into the stope before backfilling was completed (Plate XVIII)

Cave 05-B-05W - August 28, 1988

While backfilling stope 08-B-05W, the back collapsed and reached the ground surface almost immediately. The chimney followed Borehole MT 11. A fault exists in this area, and wetness was noted. Therefore, some ravelling may have been involved.

Cave 05-1-04 - August 24, 1989

The remnant pillar in stope 05-1-04 caved right up to the surface.

Cave 05-D-06 - May 2, 1990

The back failed near the southeast fault. The slab was about 5 m in thickness. This stope was blasted on April 17, 1990. Investigations showed the presence of water at the rock-overburden contact. A round of development was taken on the same fault some 15 m south (in 05-C-07). A backfill hole was drilled from the surface between May 14 and 16, 1990 and the cave was then filled.

This historical record and personal observations at the Mine indicated that sub-level caving may be an appropriate means of completely removing the surface crown pillar. The intentional cave at Stope 05-2-13 showed that the failure mechanism predicted by modelling had in fact occurred. This increases confidence in new and rational approaches to the study of surface crown pillars and encourages a closer look at, and use of, the failure mechanism concept proposed by Bétournay (1989). The success in prediction does not lie in the intricacy of the model used. Rather, it lies in the quality of the data used in the model. At Les Mines Selbaie, the rock mass and overburden soil characterization, from field, laboratory and in situ testing, was crucial to the success of the model predictions.

10.0 CONCLUSIONS

The objective of this research was to evaluate the approaches, methods, solutions, remedial measures and equipment used in the project so as to be informative firstly on a technical basis, but also to be exhaustive for transfer of technology to mine operators. This Chapter presents major conclusions of the research project in support of this objective.

The research initially was conducted to provide an assessment of the support and behaviour of 7.5 m thick surface crown pillars at the Les Mines Selbaie site. Finite element models (both 2D and 3D) were prepared and validated by comparison with cave-in "A" which occurred at the Mine site in 1983. Subsequently, the research was extended to analyze the feasibility of completely removing the surface crown pillars, without removing the overburden soils. It was felt the overburden soils were perhaps more competent than the surface crown pillar weak soil-like rock material mass, and therefore should provide for stable, or at least controllable, openings. Where recovery of the surface crown pillar was attempted by the control caving method, excellent results were obtained between predictions and actual performance of the instrumented and fully monitored trial mining operation. This experience proved that the failure mechanism concept of designing for support or recovery of surface crown pillars is valid and amenable to implementation, provided an integrated approach to design and extraction is encouraged, adopted and supported by senior management.

This research was conducted at a site characterized by geological materials significantly different from those found in "hard rock" mining. Traditional methods and rules of thumb could not be applied to these geological conditions. It was a necessity to discard empiricism and trial and error mining in order to ensure safety of workers and economy of production. Hence, an integrated rational design and data gathering approach was adopted right from the start, aided by expertise from the fields of engineering geology, rock mechanics and hydrogeology. The fact that the surface crown pillar zone at the site was not only the richest in ore values but also the weakest later entailed the involvement of the soil mechanics discipline as an important element of this integrated approach. The Mine, its management, and the geology and engineering groups can rightly take pride in pioneering the adoption of rational procedures and in implementing extraction using the failure mechanism concept in an integrated approach to surface crown pillar recovery.

From this study, the following conclusions are drawn:

1. All underground openings induce surface settlements, the extent and magnitude of which will depend on site specific details and excavation methods. The mining method adopted should recognize the impact of such potential subsidence on surface elements at the mine site.
2. Numerical models, such as those used in various preceding studies at this Mine site, are a viable and valuable source of design information, once they have been validated. In control caving, the theories of granular flow and ellipsoids of flow and motion have predicted caving to the surface successfully. This success has depended on good quality information on the nature and character of the overburden soils and the surface crown pillar rock mass, combined with a knowledge of geomechanical behaviour of such materials.
3. Numerical models must be quantitatively calibrated with experience gained in trial mining operations, before reliance is placed upon them for further production oriented mining. This requires a commitment to obtain, to maintain, and to seriously study all extraction records, in order to permit rational field modifications to occur during routine production mining. The use of design charts obtained from analyses and models must be conscientiously made to confirm their validity and to recalibrate predictive models.
4. Complete recovery of surface crown pillars is associated with inevitable ground movements, the magnitude and seriousness of which can be modelled with some confidence. The most significant factor affecting surface subsidence is the degree of bulking of overburden materials, and the ore dilution allowed during draw.
5. Surface settlements may be calculated with some reliance using numerical models prior to channel depression breakthrough. Should significant overbreak occur during excavation, the true dimensions of the excavated opening should be used in the estimation of surface settlements.

6. Settlement of the ground surface in the vicinity of existing buildings may be controlled by selective mining of the underlying surface crown pillar.
7. The existence of any free or entrapped water in a cohesionless overburden soil mass has the potential for disastrous consequences should flow occur during control cave mining. Therefore, mine sites with cohesionless overburden soils should be completely depressurized with respect to groundwater and hydrostatic pressures.
8. The influence of true or apparent cohesion of the overburden materials (due to presence of clay or due to negative pore water pressures within the soil matrix) is a significant factor in the initiation and timing of caving, which has a subsequent effect on the magnitude of the final settlement and arching within the blasted opening. Hence, the correct characterization of the overburden soil mass is an essential requirement for correct design and prediction of surface subsidence or cave-in.
9. The success of the caving method of surface crown pillar recovery depends on minimizing serious disturbance of the soil over the opening before recovery starts. Improperly sealed exploratory holes, for example, could become paths for chimney breakthrough and uncontrolled ravelling and caving.
10. The mining method selected for recovery of surface crown pillars must be accomplished in a safe and economical manner. The concept of failure mechanisms is an invaluable tool in this regards and should be used in a knowledgeable manner for successful recovery.
11. Properties of geological materials or the mass characteristics assumed in design, analysis and modelling may be different from those encountered under actual mining conditions. Therefore, the mine must exhibit a degree of flexibility and adaptiveness to accommodate such deviations and to find solutions which take into account the differences between assumed and actual conditions.

12. The trial and error method of mining is not only uneconomical, it can also be unsafe, and may no longer be acceptable in this age of advanced technology and modelling capability. Material characterization, analysis, modelling, and field observations should be applied with judgement, prudence and skill.
13. At Les Mines Selbaie, a "worst" kind of rock material was encountered in the surface crown pillar. That this material could be safely and profitably recovered without removing the overburden soil should be encouragement to other mine sites with even better rock mass characteristics in their surface crown pillars.
14. The support, or complete/partial recovery of surface crown pillars involves the overburden soils and groundwater in an interactive manner which must not be ignored and which can not be analyzed or accounted for using principles of rock mechanics alone. Hence, geotechnical engineering expertise in soil mechanics becomes an essential partnership in the analysis of strategies for surface crown pillar support and/or recovery.
15. In effecting technology transfer, the special conditions prevailing and the behaviour observed at one site should be fully understood to avoid the danger of misapplication of results to another site with totally different conditions. Hence, the underlying rationale must be fully understood and only the principles pertaining to the problem should be adopted for direct use.

11.0 GENERAL PROCEDURES FOR SURFACE CROWN PILLAR RECOVERY

One of the main objectives of this research was to make recommendations for recovery of surface crown pillars without removal of overlying soils at other mine sites. The effects of overburden thickness, variations in soil types and of surface crown pillar spans, as well as difficulties relating to extraction of the surface crown pillar masses were to be addressed.

In this Chapter the results of previous research are expanded into guidelines for general purpose application to projects involving partial or complete removal of surface crown pillars without removal of the overlying soils. These guidelines are based not only on the results of research at Les Mines Selbaie, (which has unique surface crown pillar characteristics differing widely from those normally found at other Canadian mines), but also on other geomechanical disciplines.

11.1 Introduction

The current state of knowledge of the behaviour and characteristics of surface crown pillars is not advanced, as clearly demonstrated in the state-of-the art presentation by Bétournay (1989). Therefore, any attempts at partial or complete recovery of ore from the surface crown pillar must take this limitation into account.

Complete recovery of the surface crown pillars at Les Mines Selbaie was made possible, in part, by the recognition that traditional approaches to designing of support systems and excavations would not be applicable, and that further specific research was required to overcome shortcomings in knowledge of the weak rock mass materials and overburden response during and after recovery of the surface crown pillars.

11.2 Integrated Design Approach

The principles of rock mechanics are fully applicable to hard rock mines. However, they are of limited use in mines with weak soil-like rock masses. Gaps in knowledge need to be supplemented from principles of soil mechanics and other related disciplines, not traditionally considered in routine mining operations.

This requires an integrated approach to resolving problems when geological conditions are not those with which one may be familiar or with which past successes may have been achieved. The project at Les Mines Selbaie offered a unique opportunity to utilize both soil and rock mechanics principles for the development of specific solutions. The recommendations given in this Chapter are adopted from that experience and from the sparse published literature on the subject.

11.3 Design Process

Bétournay (1989) offers the following definition of a surface crown pillar:

A rock mass of variable geometry, mineralized or not, situated above an uppermost stope of the mine, which serves to permanently or temporarily ensure the stability of surface elements.

When the surface crown pillar is completely removed, all that remains is the overburden. Therefore, the behaviour of the overburden must be predicted and suitably controlled to prevent failures. If, as in some cases, a nominal thickness of "residual crown pillar" is left below the overburden contact, then the properties of both the residual pillar and the overburden soil are important, both individually and collectively due to their interaction with one another.

Figure 6 shows a preferred design process for surface crown pillars (Bétournay, 1989). The flow chart represents a desirable scenario for all mine sites, but in practice it is seldom followed in the manner depicted, for various reasons. Tradition, past experience and contingencies of mining operations often preclude strict adherence to the process illustrated. Since surface crown pillars lie in a very special category of their own, a structured project advance approach is required, based on representative geomechanical data from all soil and rock units.

Studies to date, including the research performed at Les Mines Selbaie, show that successful design for recovery of surface crown pillars depends to a very large extent on a full understanding of the overlying soil mass. In traditional mining, little attention is paid to the overburden, except in projects involving open pit mines where the steepness and stability of the cut slopes in the overburden become a critical economical factor.

Therefore, an understanding of overburden material characteristics and performance under various states of stress is an essential requirement of successful surface crown pillar recovery.

11.4 Overburden Characterization

Table 5 gives a suggested classification of overburden types and their significant features with respect to surface crown pillar recovery. The classification is, of course, greatly simplified for purposes of illustration only. However, the suggested classification will serve as a first guide in determining appropriate methods of analyses.

In Table 5, a major distinction is made between two basic types of mineral soils - cohesive and non-cohesive. Non-cohesive soils are those whose grains are not bound together by physico-chemical forces, and whose strength and compressibility are simply a function of the way in which the individual particles are packed together. Cohesive soils are those in which the clay mineral plays a significant role, with attendant physico-chemical characteristics which influence its shear strength, compressibility and time rate of strain under any given state of stress.

Organic soils are characterized by lack of mineral content, high moisture retention capacity and very high compressibility under applied stress. They are known generically as swamps and muskegs, but consist mainly of peats of various types - from muck (100% decomposed peat) to amorphous to fibrous to woody, depending on genesis and paleontology. A majority of peats in the low lying areas of Canadian mine sites are generally fibrous, with woody portions present only in the upper 1 m to 2 m of the soil profile. Organic soils possess little shear strength which can be mobilized to create stable openings. It is therefore recommended under "Preferred Treatment" in Table 5 that such soils be removed from above the surface crown pillars to be recovered.

On the other hand certain options are available for inorganic mineral soils, which may be either removed completely or left in place with modifications as shown in Table 5 and explained in further detail in Section 11.8 of this report.

The "Technical Concerns" in Table 5 refer to likely effects of surface crown pillar removal on the overburden soil and hence on the underground opening.

Table 5. Key Design Considerations of Overburden for Surface Crown Pillar Recovery

OVERBURDEN TYPE				
Organic Soils	Mineral (Inorganic) Soils			
	Cohesive		Non-Cohesive	
	Soft	Stiff	Loose	Dense
<u>Preferred Treatment</u>				
Remove	Remove Strengthen	Leave	Remove Densify	Leave
<u>Technical Concerns</u>				
Cave	Subsidence Collapse	Stability Subsidence	Liquefaction Subsidence	Ravelling Subsidence
<u>Nominal Stope Width</u>				
0m	0 - 2m	1 - 5m	0m	3 - 10m
<u>Probable Stand-Up Time (Days)</u>				
0	1 - 2	7 - 300	0	1 - 200
<u>Likely Mode of Failure</u>				
Collapse	Shear Slough	Shear Block	Flow Cave	Arching Cave-in
<u>Groundwater Effects</u>				
No concern	Some concern	Of concern	Much Concern	Of Concern
<u>Modes of Analyses</u>				
N/A	Viscous Flow	Plastic Breakthrough	Viscous Flow	Plastic Breakthrough

The nominal stope widths shown in Table 5 are provided only for guidance and for an appreciation of the difference in character between the four inorganic soil groups listed. The nominal widths shown may be used for economic evaluations but should never be used in design. Stope widths, lengths and heights should be determined on the basis of an integrated design approach which accounts for all of the possible failure mechanisms, and only after the overburden character has been assessed with a known degree of confidence.

In both cohesive and non-cohesive mineral soils, the pore water pressure is a significant component of shear strength, and in terms of surface crown pillar recovery, affects greatly the "stand-up" time of openings. Pore pressures will dissipate or recover rather rapidly in non-cohesive soils (unless their permeability is extraordinarily low due to very dense packing or appreciable silt content). In cohesive soils, the pore water pressures will take a much longer period of time in which to dissipate or recover, thus exerting a temporal influence on the behaviour of the overburden. In practice, stand-up time is also influenced by "soil arching" which can occur in very stiff to hard cohesive soils and all dense non-cohesive soils. The stand up time in days shown in Table 5 refers to stand-up time both due to pore water pressure influences and due to soil arching effects. Positive pore water pressures can destroy the beneficial effects of soil arching in non-cohesive dense soils.

Figure 23 illustrates the likely modes of failure possible below the various overburden soil types. The failure severity and time to failure will depend to a very large extent on the character of the overburden soil mass, its pore water pressure characteristics, the method of mining, stope design and the manner in which surface crown pillar recovery is effected.

Experience at Les Mines Selbaie shows that initial assessment of likely modes of failure can be made by the use of two dimensional base friction modelling (Goodman, 1976; Strata Engineering Corp., 1987). In this technique the soil or rock mass material character is modelled with a mixture of flour, sand and oil (and other additives as necessary). The mixture is spread on a wide belt of sandpaper. Gravity loading is simulated by rotating the sandpaper on a rigid frame while holding the flour-sand-oil mixture in place after creating a desired shape of opening within the spread mixture. Planed lumber may be used to form a "guide" representing the orebody geometry (dip, width, size of opening, etc.). From such modelling, appropriate finite element discretization can be selected for numerical analyses.

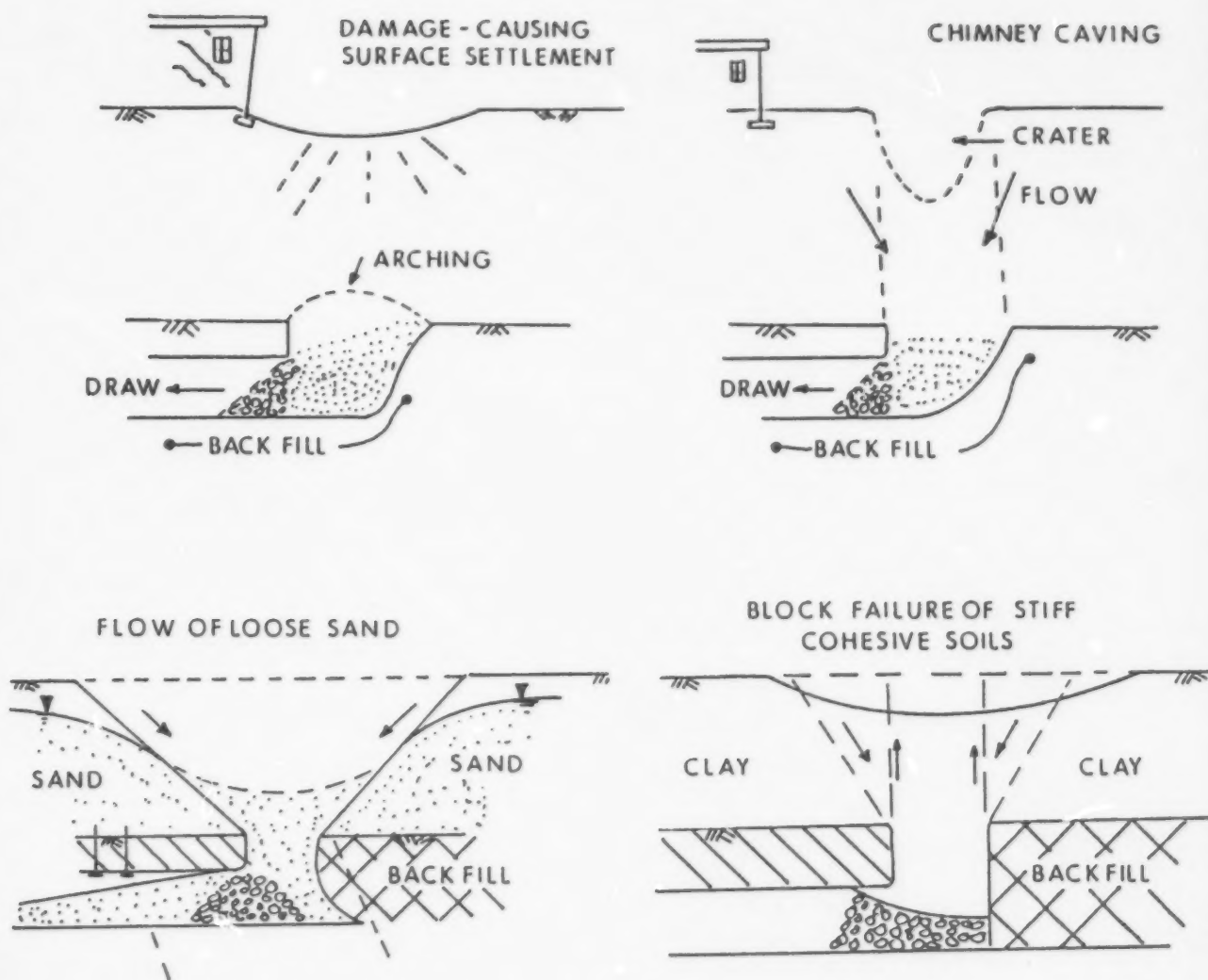


Figure 23. Possible Modes of Failure

The field testing and key parameters required for design of stable openings below overburden soil masses are shown in Table 6. SPT stands for the Standard Penetration Resistance Test which is usually acceptable only in very stiff to hard cohesive soils and in all types of non-cohesive soils. CPT stands for the Cone Penetration Test, generally performed in soft cohesive or loose non-cohesive soils. P'meter stands for either pressuremeter or dilatometer types of in situ testing, generally performed in stiff or dense formations, or in those formations where recovery of samples for laboratory testing is either difficult or results in large disturbances upon recovery.

Reference to strength of soils under Key Design Parameters in Table 6 refers not only to shear strength but also to stress-strain behaviour, pore water pressure effects, angles of internal friction and cohesion intercept. These parameters are required as inputs to analyses and numerical models.

Table 6. Minimum Field Testing Requirements and Key Design Parameters.

	OVERBURDEN TYPE			
	Organic Soils		Mineral (Inorganic) Soils	
			Cohesive	Non-Cohesive
	Soft	Stiff	Loose	Dense
<u>Field Testing</u>				
SPT	No	Yes	Yes	Yes
CPT	Yes	N/A	Yes	N/A
P'meter	No	Yes	No	Yes
<u>Key Design Parameters</u>				
Moisture	Yes	No	Yes	No
Plasticity	Yes	Yes	No	Yes
Strength	Yes	Yes	No	Yes
Permeability	Yes	Yes	Yes	Yes
Modulus	Yes	Yes	No	Yes

In nature, overburden soils seldom fall neatly into the four categories shown in Figure 23. More often than not, the overburden soils found at Canadian mine sites have been influenced by continental glaciation (pleistocene events) and subsequent modification (holocene events). Therefore, a proper assessment of their character and likely behaviour, through geotechnical investigations and analyses, is an essential first requirement towards any planned recovery of surface crown pillars without removal of the overlying soils.

The methods of analysis adopted for prediction of behaviour will depend on the type of soil, groundwater conditions, and method of mining proposed. For example, blasting close to the contact between overburden and rock in loose soils could cause liquefaction flow. If sensitive soft clays are present in the overburden, some types of vibrations from blasting operations could cause them to liquefy or to lose a major proportion of their in situ strength.

11.5 Site Investigations

In this section, guidelines are provided to ensure that a minimum standard of investigative effort is applied to the determination of overburden characteristics. In any intended recovery of surface crown pillars, the most important step is to recognize the existence of any overburden soils above the remnant pillars and to account for their behaviour prior and subsequent to extraction.

It is necessary to undertake proper "geotechnical" types of site investigations to determine as a minimum the strength, compressibility and time rate of deformation characteristics of the overburden soils. These features are often determined from field investigations, observations and laboratory testing procedures (Dowding, 1978).

As a minimum, the following must be fully known:

- types of overburden materials, and their extent, thickness, and relationships;
- nature of materials (whether cohesive, non-cohesive, soft, hard, loose, dense, &c.);
- physical properties (grain size, plasticity, moisture content, &c.);
- engineering properties (friction, cohesion, preconsolidation, pore pressure, &c.).

A proper site geotechnical investigation involves drilling, sampling and in situ testing procedures such as those described in CGS (1985). It is not the intent of this chapter to repeat what is already published and readily available. The reader is referred to previous research reports and published papers on innovative field techniques which have resulted from this research program to enable recovery and in situ testing of weak soil-like rock masses at or near the overburden-rock contact. As a minimum, the overburden characterization study should cover an area, A, at the surface given by equation [3]:

$$A = W \times 12L \quad [3]$$

where:

- A = minimum area of surface site investigation
- W = minimum exploration corridor width orthogonal to orebody strike
- L = length of ore body along the strike direction
below which recovery is planned

The value of W can be determined from equation [4]:

$$W = [d \cdot \tan \theta + B + 2(D + d) \cdot \cot \theta] \quad [4]$$

where

- d = thickness of surface crown pillar
- D = maximum thickness of overburden along strike of orebody
- B = maximum thickness of ore body mass along length, L
- θ = steepest dip of orebody

Example

Given:

Orebody thickness	10 m
Dip of Orebody	50°
Length of Orebody	100 m + 20% = 120 m
Surface crown pillar thickness	15 m
overburden thickness	25 m

Solution:

From equations [3] and [4] $W = 95 \text{ m.}$

Hence, the surface exploration of overburden characteristics must extend laterally about 50m on either side of the orebody, orthogonally to the strike direction. The number of boreholes to be drilled for overburden characterization will depend on geological information about the site and the probabilities associated with depositional variabilities.

In uniform geological formations, it is best to drill and sample boreholes at maximum intervals of about $0.7W$ along the orebody strike in a zig-zag pattern to enable sampling of the full corridor width. In more complex stratigraphies, the borehole interval should be reduced to $0.5W$ and in severe cases to as low as $0.33W$.

At most developed mine sites, surficial geological data will already be available. Site specific geotechnical studies performed during mine development for the design of foundations of buildings, processing plants and shafts may be available for re-use in evaluating the overburden characteristics for surface crown pillar design and/or recovery purposes, provided the boreholes previously drilled coincide with the area of interest.

More often than not, and excepting for deep shaft or adit locations, the traditional geotechnical studies for foundations of buildings, plants, tanks and similar surface elements of the mine would proceed normally to depths of about $3b$ where b is the footing width used in the foundation. In softer ground, where pile support is required, the depth of borings and sampling will of course have been extended to a competent bearing strata such as the bedrock.

In order to ensure that the nature and character of the overburden across area A is reliably understood, a soil boring and sampling program must be initiated, if previous available data are found to be lacking or deficient in terms of coverage, depth, or detail.

In non-cohesive overburden, samples should be obtained at minimum depth intervals of 1.5m. Normally the Standard Penetration Resistance Test is used to recover relatively disturbed soil samples. The N values accompanying such tests should be recorded for each sample. It should be noted that the sampler used in this test has an internal diameter of about 35 mm. Thus, all particles larger than 35 mm in equivalent diameter are omitted from the sampling device.

The presence of large gravel sizes, cobbles and boulders can not be determined by standard split-spoon sampling of the overburden. In traditional geotechnical practice, an experienced overburden driller performs the drilling, under supervision from a trained geotechnical engineer or technologist who can "listen" to the machine and by observations of the behaviour of the sampler during the SPT test, infer the presence of such larger sized particles in the stratum being sampled. Alternatively, larger diameter samplers could be employed to extract coarse grained soil samples from the overburden. However, the energy required for penetration of such samplers is much higher than that for SPT testing, and very few correlations are available between the N values obtained from SPT testing and blow counts from the use of other sampler sizes and driving energies.

Hence, traditional, mine-based drillers, not experienced in overburden drilling and sampling, should be allowed to carry out overburden characterization studies only with the full time presence of, and direction from, an experienced geotechnical engineer or technologist.

In cohesive deposits, thin walled tube sampling is preferred, unless the deposit is very stiff to hard in consistency and overconsolidated, in which case the Standard Penetration Test method of sample recovery is acceptable, with exceptions as dictated by the nature of the problem. In softer cohesive soils or in less dense and finer grained non-cohesive soils, continuous in situ testing and soil characterization may be possible using piezo-cones and cone penetrometers. Such devices are normally not available at mine sites and may need to be specially mobilized.

In soft to stiff cohesive deposits, in addition to thin walled tube sampling, in situ undrained vane shear strength tests should be conducted as a matter of routine after each sample is withdrawn. In soft to very stiff clays, both undisturbed and remoulded shear strength measurements should be made to evaluate the sensitivity of the soil (defined as the ratio of undisturbed to remoulded undrained shear strength).

The primary objective of the overburden soil sampling program should be to delineate with as much confidence as possible the various soil strata across the area being investigated. The intensity and frequency of sampling and testing will be determined by factors such as:

- local knowledge of geology
- previous experience at the site
- availability of previous reliable information
- confidence in the continuity of strata in the horizontal plane
- confidence in stratigraphic boundaries
- the materials being sampled, and
- groundwater conditions

11.6 Material Characterization

Material characterization should include both overburden and surface crown pillar soil and rock materials respectively. Geotechnical investigations should be extended deeper to include the surface crown pillar rock mass. The attributes of the rock mass, such as compressive strength, modulus of elasticity, modulus of deformation, and other engineering parameters should be established, either from cores taken in the rock mass and from in situ testing.

11.6.1 Cohesive Overburden

In cohesive soil strata, the following parameters should be determined for each stratum, as a minimum:

- Moisture Content and Atterberg Limits (state of plasticity of soil)
- Liquidity Index and Sensitivity
- Clay content (as per cent by weight of total mass, by hydrometer analyses)
- Undrained shear strength
- Drained shear strength (from Direct Shear Tests or Triaxial Tests)
- Pore pressure characteristics and A coefficient at failure
- Poisson's ratio (generally 0.3 to 0.5 depending on consistency)
- Modulus of Elasticity (Undrained, Drained, Secant, Tangent)
- Preconsolidation Characteristics (P_o , C_r , C_o , e_o)
- Effective Cohesion Intercept, c'
- Effective Angle of Internal Friction, ϕ'
- Unit weight (γ), and Specific Gravity (G_s)

11.6.2 Non-cohesive Overburden

In non-cohesive soil strata, the following parameters should be determined:

- Grain Size Distribution (per cent gravel, sand, silt and clay)
- Grading characteristics (uniform, skip graded, well graded) and Relative Density
- Moisture Content
- Effective Angle of Internal Friction
- Moduli of Elasticity and Deformation
- Dilatancy and pore pressure response to shear stresses

In many instances, past experience in the area or with similar materials can yield nominal values for design purposes. If numerical modelling is to be performed as part of the design process, then a range of assumed values can be used for parametric studies. Such studies are important in the recognition of key material properties, at which time further detailed testing can be conducted. For example it may be assumed, for initial design evaluation purposes, that the effective angle of internal friction of a dense sand is 38° .

This value may vary by $\pm 4^\circ$, depending on a number of characteristics such as:

- grain size distribution and packing density,
- nature of the particulate matter (sharp or well rounded),
- mineralogy (quartzitic or feldspathic),
- sampling disturbance,
- method of testing,
- operator error,
- interpretation of test results, etc.

If this parameter (effective angle of internal friction, ϕ') is not critical to the design process, then any expense involved in its accurate determination is not justified.

The selection of type of testing and evaluation of an overburden stratum is a function of the nature of the material, the anticipated mode of failure, and the significance of the property to be evaluated on the failure mechanism. Hence, soil testing can not be conducted in isolation from the overall requirement for design, and therefore must become an integral component of the integrated design approach.

It is also a matter of good engineering practice to conduct what are known as "Index Property" tests on representative soil samples from the overburden for classification purposes. Some index properties can then be used to interpret engineering characteristics. For example, a clayey soil which has a natural moisture content close to or lower than its plastic limit, is most probably overconsolidated.

It is generally good practice to arrange the recovered soil samples in the laboratory for detailed examination of each. Wherever possible, each sample should be cut in half lengthwise to determine its stratigraphic texture, and hence to infer its depositional origins. For example, a sand with a given grain size distribution pattern may have an angle of internal friction quite different from a sand having an identical grain size distribution, for reasons given above. Hence, visual examinations of all recovered overburden samples should be a mandatory requirement of the geotechnical engineering process involved with overburden assessment for surface crown pillar recovery.

A number of publications in the soil mechanics field are available and these should be consulted for a more detailed treatment of the subject.

11.7 Methods of Analyses

The methods chosen for the analysis of a given problem will depend on many factors, such as the nature of the problem, significance to safety and economy, reliability of the data being used in the analysis, and the applicability of the solution to the problem being analyzed. An integrated approach to the analysis of a problem is required for overburden characterization. One can not isolate the overburden material character from the method of analysis. The nature of the overburden materials will dictate the most likely modes and mechanisms of failure, and these in turn will dictate the analytical methods required to resolve the problem.

Failures in overburden masses may be classified as catastrophic (eg. caving to surface with destruction of surface elements), disturbing (eg. settlement in excess of tolerable limits for the surface element) or nominal (eg. no effect on surface elements). A cave-in which runs up to the ground surface but does not affect surface elements, however, can not be classified as catastrophic.

Therefore, the use of the terms catastrophic, disturbing and nominal should be kept in proper perspective in relation to surface effects.

Below the ground surface, at the ore recovery or extraction level, the effects of overburden failure may again be classified as catastrophic, disturbing or nominal. Any failure which threatens life may be termed catastrophic. A failure which results in economic loss (for example, high ore dilution) may be described as disturbing, and a failure which causes little inconvenience to normal operations may be termed nominal.

The types of failures to be analyzed range from the catastrophic to the nominal. The intensity or complexity of the analysis will depend on how one perceives and classifies the potential effects of failure, either on the surface or below ground.

Surface settlements of the overburden, due to caving or extraction of the surface crown pillar, progress through three stages, namely: 1) Elastic, 2) Plastic settlement before surface break through, and 3) Plastic settlement with surface break through.

11.7.1 Elastic settlement

The magnitude of this type of surface settlement is very small, and can be predicted by elastic theory. During this stage, no failure of the overburden medium occurs and the underground opening remains stable.

11.7.2 Plastic settlement before surface breakthrough

1. Non-cohesive overburdens

During continuous extraction of ore from a stope the overburden will begin to flow into the stope under the influence of gravity, causing the development of an ellipsoid of motion, and a corresponding limit ellipsoid (see Figure 12).

The size of this ellipsoid will grow progressively towards the ground surface with further extraction of ore. As long as the limit ellipsoid, which defines the extent of the ground movement, does not break through the ground surface, surface subsidence can be predicted by means of large strain elasto-plastic models with a bulking factor modification.

2. Cohesive Overburdens

The behaviour of cohesive overburden soils resulting from underground ore extraction is a complex subject, and its assessment depends on the nature of the overburden mass. Experience from tunnelling in soft ground shows that surface settlements follow an inverse probability distribution curve (Figure 9). This approximation is useful for initial assessment of ground behaviour, and will indicate whether or not more complex 2D or 3D finite element modelling is required.

11.7.3 Plastic settlement with surface breakthrough

With continued ore extraction, a limit ellipsoid will eventually break through the ground surface causing the formation of a surface crater. Under these circumstances, large strain elasto-plastic models become inappropriate. It is then necessary to examine other methods of analyses, or to develop new models to predict such failures.

11.8 Ground Modification

In assessing the suitability of overburden conditions for recovery of surface crown pillars, the possibility of modifying the overburden behaviour characteristics by ground modification techniques should not be overlooked (ASCE, 1978). Factors to consider in ground modification are:

1. Will the process be economical in comparison with other alternatives (eg. complete removal)?
2. Will the process endanger the safety of the surface crown pillar zones of the mine (eg. destabilize residual pillars)?
3. Is the process the correct one to use for the conditions being encountered?

Several advances have been made in recent years in ground modification theory and application, for both cohesive and non-cohesive soils (Mitchell, 1968). Non-cohesive soils which are loose and subject to liquefaction failure could, for example, be densified by vibratory compaction to depths of up to 15m below ground surface, using in situ techniques or to shallower depths using surface techniques.

Soft cohesive soils could be made stronger by reducing their moisture content through active in situ drainage (eg. wick drains), or by electro-osmosis (Casagrande, 1952; Lo and Ho, 1991).

Any intended ground modification process will have both positive and potentially negative impacts respectively on the strata being modified and other strata which may be present adjacent or below. Therefore, a thorough review should be made of not only the problem to be resolved but also of the problems which might be unintentionally created when a solution is applied to resolve the original problem.

Ground modification should be viewed as a solution of last resort. Parametric studies provide the flexibility to examine both existing in situ and future modified overburden material characterization. They are thus useful design tools to examine a range of alternatives.

Finally, any ground modification proposal should be accompanied by:

1. Field trials
essentially to confirm that the methodology is applicable to the site conditions.
2. Confirmation of effectiveness
by monitoring and interpretation of the results obtained
3. Monitoring to ensure quality

Potential impacts of ground modification on regions below the rock-overburden contact should not be overlooked.

12.0 SUMMARY OF DESIGN APPROACH

In planning complete recovery of surface crown pillars, three basic questions need to be answered:

1. Is the ore valuable enough to be extracted in this zone?

As a rule of thumb, it may be impractical or uneconomical to recover ore from the surface crown pillars, if the ore values are not at least two to three times as great as those below the surface crown pillar zone. The economics of a given percentage of ore recovery safely must be carefully determined, with generous allowances for unseen factors. At Les Mines Selbaie the planned profit was in the neighbourhood of \$1.5 million. The actual profit realized was about 1/7th of this, for reasons other than a technical inability to recover the ore from the surface crown pillar zone. This shows the need for extreme conservatism in planning and assessing the financial feasibility of ore recoveries from surface crown pillars, specially without removal of overburden. If the answer to this question is Yes, then the next question to be answered is:

2. Are conditions safe for the proposed recovery?

Before starting recovery, an assessment should be made of the pillars and openings to ensure that they are in a stable condition. This is to ensure that no failures have taken place or are anticipated. At the same time, consideration should be taken of whether or not the proposed recovery method will be too slow or progress at such a rate that a thinner pillar created might become unstable during the recovery process. For example, it may be safer to effect removal in one large blast than by slashing in thin sections in those situations where time is a factor in the stability and safety of openings created during ore recovery (see 3.2 below).

If the answer to this question is yes, then the next question to be answered is:

3. Can the ore be recovered safely?

The answer to this question will depend on a number of factors and considerations, the most important of which are discussed in some detail below.

3.1 What is the geometry of the ore body and the character of the overburden?

The geometry of the ore body includes width, dip angle and the relative juxtaposition of surface facilities with respect to the ore body location below ground. The overburden character can be determined from site investigations and testing, as discussed in Sections 11.5 and 11.6. The ore body geometry will, in the first place, dictate the method of recovery and mining strategies. In flat lying ore bodies room and pillar mining may be more appropriate, whereas in sloping ore bodies, cut and fill may be the safest method of ore extraction. The method of ore recovery will therefore depend on the proper characterization of ore body geometry and overburden soil characterization.

3.2 Which method of recovery is likely the best given these ground conditions?

There are several ways of recovering surface crown pillars (cut and fill, flatback stoping, drill and blast, etc.). The method chosen should be compatible with the ore body geometry and overburden character. The time factor involved with the proposed extraction method must be fully addressed, since in some types of overburden soils the time available for stability of a newly created opening below the overburden contact is always an important consideration.

3.3 Can the method of recovery be tested on paper to determine success or failure?

This is an important preliminary exercise to safeguard against predictable failures, and to anticipate potential deformations which might affect surface facilities (see Chapter 7). A decision should be made as to whether or not the overburden should remain in place (either as is, or after modification - see Section 11.8), and if not, what would be the safest and most economical way for its partial or complete removal?

3.4 What data are required for analyses?

A determination should be made of data on hand and data required for proper assessment of the surface crown pillar and overburden characteristics. Table 6 will serve as a useful guide or checklist in ensuring that the minimum required data for overburden soil characterization are available for the appropriate types of overburden behaviour analyses. The analyses should be appropriate to the method of mining most likely to be adopted, based on a consideration of the answers from 3.1 and 3.2 above.

3.5 Are the data obtained: complete, representative, reliable?

Incomplete data can be not only misleading but also dangerous due to a temptation to make untested assumptions regarding the missing information. Data must be representative of the stratigraphic units. Replication is a good way of testing data reliability, combined with a literature review to ensure that the values being obtained at the mine site for any given material characteristic are within the range of values normally expected of similar geological materials. Both laboratory and in situ testing are recommended to ensure that a check is available on the measured values. Large discrepancies should be explained rationally (eg. sampling disturbance may yield a laboratory test value for a given parameter lower than that obtained for the same parameter by in situ tests).

3.6 What analyses are suitable for the method of mining proposed and the character of the ground, as determined from the data acquired?

The method of analysis must satisfy the in situ and proposed mining conditions. The method of analysis must be carefully selected to be as representative as possible of overburden and surface crown material characteristics and potential behaviour, for the intended method of mining and recovery. The difference between plastic and elastic deformations and behaviour should be appreciated. Time dependent behaviour must be accounted for. Strain hardening or softening must be understood for the material being analyzed. Every geological material has certain characteristics whose behaviour will depend on the prevailing and modified stress field resulting from changes brought about by the mining methodology proposed. This mechanism must be clearly understood and applied in any analysis of the problem.

3.7 Do preliminary analyses show the need for more complex analyses?

Preliminary analyses may be performed using analytical solutions, simple models (Hoek, 1989), and 2D finite element analyses. If these show factors of safety or degrees of probabilities of failure which are marginal, then it may be worthwhile to conduct more refined and more complex analyses to gain confidence, or to render correct decisions.

3.8 Is the acquired data sufficient for more complex analyses?

More refined or complex analyses may require new data. Parametric studies are an economical means of establishing such data needs.

3.9 Can the predictions be confirmed under actual conditions?

Analyses and models should be calibrated to ensure confidence in their appropriateness. Calibration can be achieved by trial mining procedures, or from well documented and reliable case records from the mine. Where predictions and actual experience are at great divergence, the methods of analyses must be re-examined and adjustments made to ensure that the appropriate failure mechanisms are adequately addressed.

3.10 Is the trial mining reflective of production mining to be used later?

Trial mining conducted for the purpose of model verification, or determination of actual failure mechanisms, should in all instances reflect production methods to be used later. Predictions made and calibrated on the basis of one method of surface crown pillar recovery will not come true if during production mining a totally different method of recovery is adopted.

3.11 Is the site monitored properly for field trial data to be acquired?

When field trials are conducted, sufficient instrumentation and monitoring resources should be allocated to compare the behaviour of the soil and rock mass with that predicted from the modelling. This will help in calibrating the model for production mining.

3.12 Is the instrumentation: valid, adequate, calibrated?

Any instrumentation installed for monitoring overburden and surface crown pillar behaviour during complete or partial recovery through trial or production mining must be: valid in terms of its intended function, adequate in terms of site coverage and replication, and calibrated beforehand to ensure the data collected is correct. A knowledge of the most likely failure mechanism is invaluable in making the proper assessment of instrumentation types and numbers, location, accessibility and protection.

3.13 Are ground control and other safety requirements in place?

No matter how sophisticated the method of analysis and prediction, nature holds surprises that no one can fathom in advance. Therefore, in addition to normal mine safety measures, additional precautions may need to be taken, such as removing cars from a parking lot situated above a trial or production stope from which the surface crown pillar is to be recovered, even if the modelling or analysis predicts that there will be no chimney caving to the surface.

3.14 How well did the analyses reflect actual field trial performance?

A comparison should be made between prediction and outcome, to examine differences and similarities. It should be recognized that a perfect match between prediction and actuality may be a coincidence. Therefore, rational reasoning should be employed to accept or reject both similarities and differences.

3.15 What level of confidence is justified in the analyses performed?

Based on the results at hand, judgement should be applied, both personal and technical, to assess the results obtained. Data coverage, adequacy, assumptions made, degree of instrumentation and all of the factors discussed above can play an important role in establishing the level of confidence in the appropriateness of the analysis used.

3.16 Is experience from the past at odds with the analyses?

If past behaviour has been different from behaviour noted during trial mining or in the analyses, all boundary conditions must be carefully examined. Perhaps, in an earlier time, the groundwater table was higher than it was at the time of the trial mining or at the time of the site investigation or at the time of material characterization. What impact has this had on material behaviour? This once again shows the importance of using a rational approach to problem resolution, rather than an empirical one.

3.17 Are there any other features which must not be overlooked?

This calls for full cooperation between planning, production and engineering at a mine site. Poor communications may lead to disastrous results.

3.18 Is the above process fully and understandably communicated to senior management?

Senior management should understand the methodology being proposed and the rationale behind it. Often, their experience and judgement are invaluable in asking the right questions.

3.19 Does senior management endorse the approach taken?

By endorsing a proposed action, senior management accepts responsibility for the outcome.

3.20 Are resources available to implement the plan of action?

Lack of resources may require short cuts to be taken or assumptions to be made which may not be valid or applicable. The risks associated with such short cuts should be carefully communicated to management responsible for decisions and the allocation of resources. Personnel involved in the process of surface crown pillar recovery, from the drilling and mucking crews underground to the staff above should all understand the requirements for safety and production. Any innovative procedures, not formerly tried at the mine site and with which miners and staff may not be familiar, should be carefully explained before the act of recovery commences. In this respect, formal training and practice may be necessary and vital to the success of a hitherto untried proposed ore recovery program.

Once these questions are answered, the mine has in hand a blueprint for success.

Such was the case at Les Mines Selbaie.

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R. C. Bryce, Manager

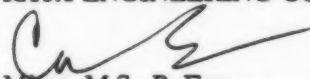
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Respectfully submitted:

STRATA ENGINEERING CORP.



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Project Manager

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APPENDIX

NOTATIONS

ABBREVIATIONS

PLATES I TO XVIII

Les Mines Selbaie Ore Recovery
Records and Laser Surveys
Drawing.

NOTATIONS

The following symbols are used in this report:

Symbol	Description	Units
A	Minimum Area for Site characterization Study	ha, m ²
A _t	Skempton's A coefficient at Failure (Triaxial Test)	
a	Radius (or equivalent) of Underground Opening	m
B _n	Minor Axis of Ellipsoid of Motion	m
b _G	Minor Axis of Limit Ellipsoid	m
C _c	Compression Index (Oedometer Test)	
C _r	Recompression Index (Oedometer Test)	
c'	Effective Cohesion Intercept	kN/m ² (kPa)
D	Max. Thickness of Overburden along Strike of Orebody	m
d	Thickness of Surface Crown Pillar	m
E _n	Volume of Flow Ellipsoid	m ³
E _s	Volume of Limit Ellipsoid	m ³
e _o	Initial Void Ratio	
G _s	Specific Gravity (also known as relative density)	
h _G	Major Axis of Limit Ellipsoid	m
h _N	Major Axis of Ellipsoid of Motion	m
I ₂	Slake Durability Index - 2 Cycles	%
i	Standard Deviation of Settlement Curve	
K	An Empirical Coefficient	
L	Length of Orebody in Strike Direction	m
n	An Empirical Coefficient	
P	Pitch (distance between two adjacent openings)	m
P _c	Maximum Preconsolidation Pressure (Oedometer Test)	kPa
PI	Plasticity Index = w _L - w _p	%
V	Theoretical Volume of Material Removed	m ³
ΔV	Volume of Settlement Trough	m ³
v	Volume of "Lost Ground" Equal to Settlement Curve	m ³
W	Minimum Exploration Corridor Width	m
w	Natural Moisture Content	%
w _L	Liquid Limit of Soil	%
w _p	Plastic Limit	%
z	Depth along Vertical Axis	m
δ	Bulking Factor	
γ	Unit Weight of Soil or Rock	kN/m ³
δ	Settlement	mm, m
δ _{max}	Maximum Settlement	mm, m
θ	Steepest Dip of Orebody	degrees
ν	Poisson's Ratio	
φ'	Effective Angle of Internal Friction	degrees

ABBREVIATIONS

The following abbreviations are used in this report:

Symbol	Description	Units
CPT	Cone Penetrometer	
N	Standard Penetration Resistance Test	Blows/0.3 m
NP	Non-plastic	
NSR	Net Smelter Return	\$
P'meter	Pressuremeter, Dilatometer	
PVC	Polyvinylchloride	
SPT	Standard Penetration Test	
QFC	Quick Field Classification System	
g/t	grams per tonne	
tpd	tonnes per day	MT ⁻¹
t	tonnes	M

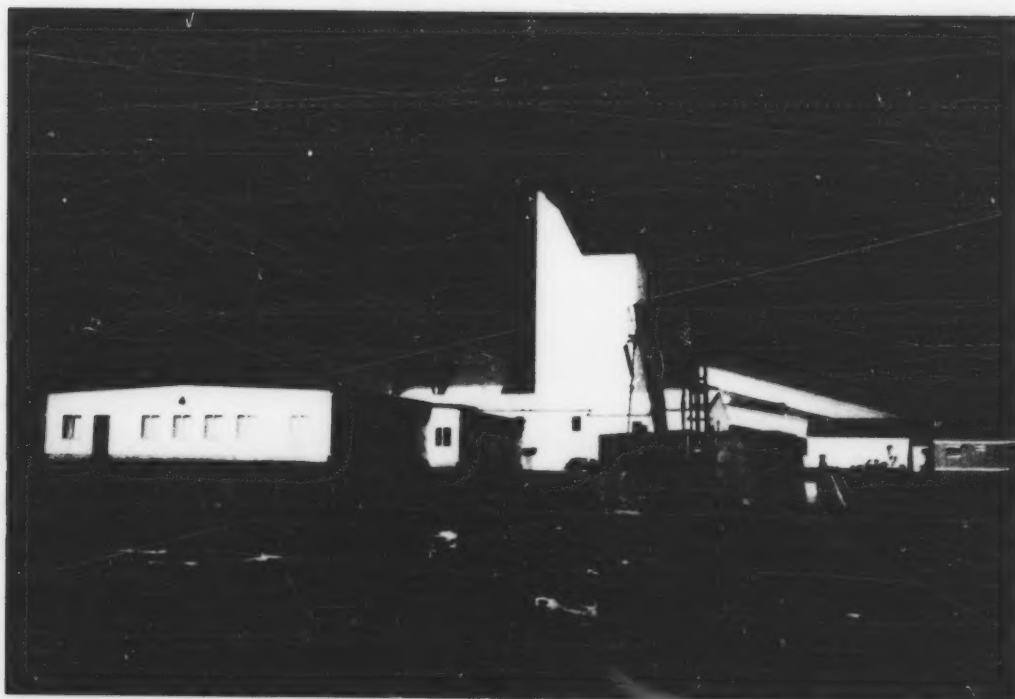


Plate I. View of Head Frame, Les Mines Selbaie.

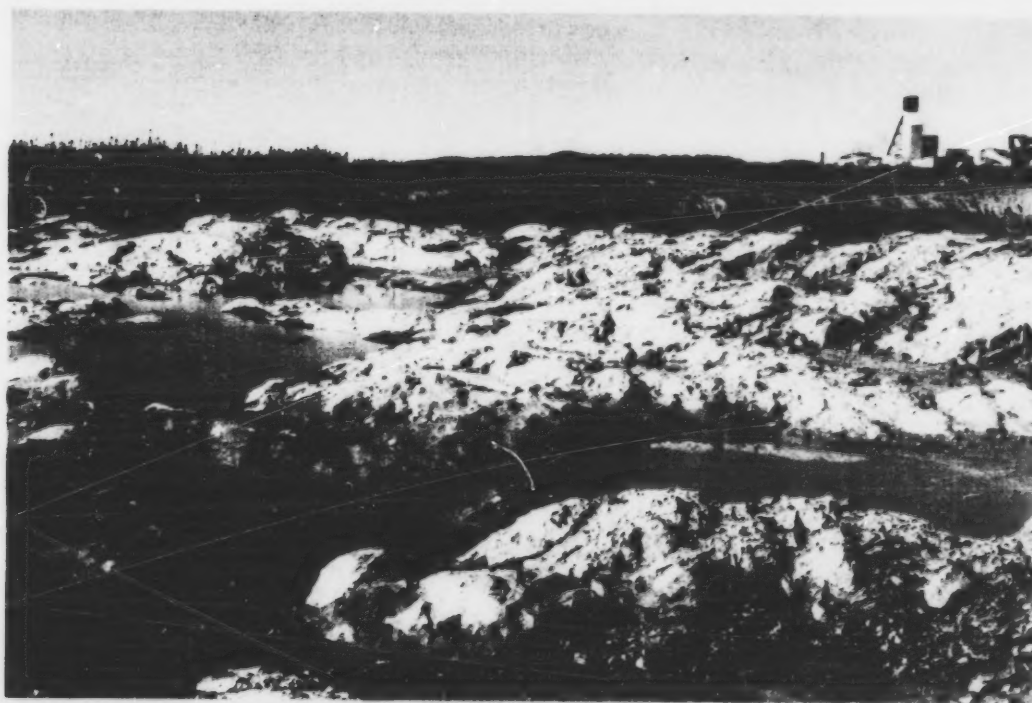


Plate II. Bedrock at surface of A-1 Zone. View looking west towards B zone.

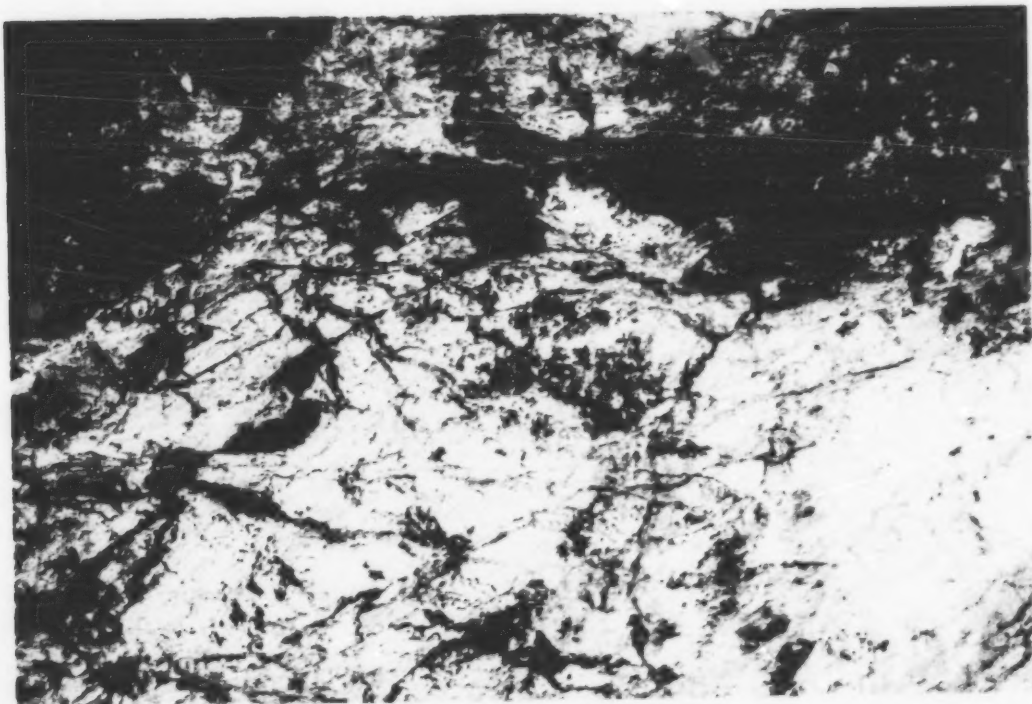


Plate III. Moderately kaolinized ore body rock mass

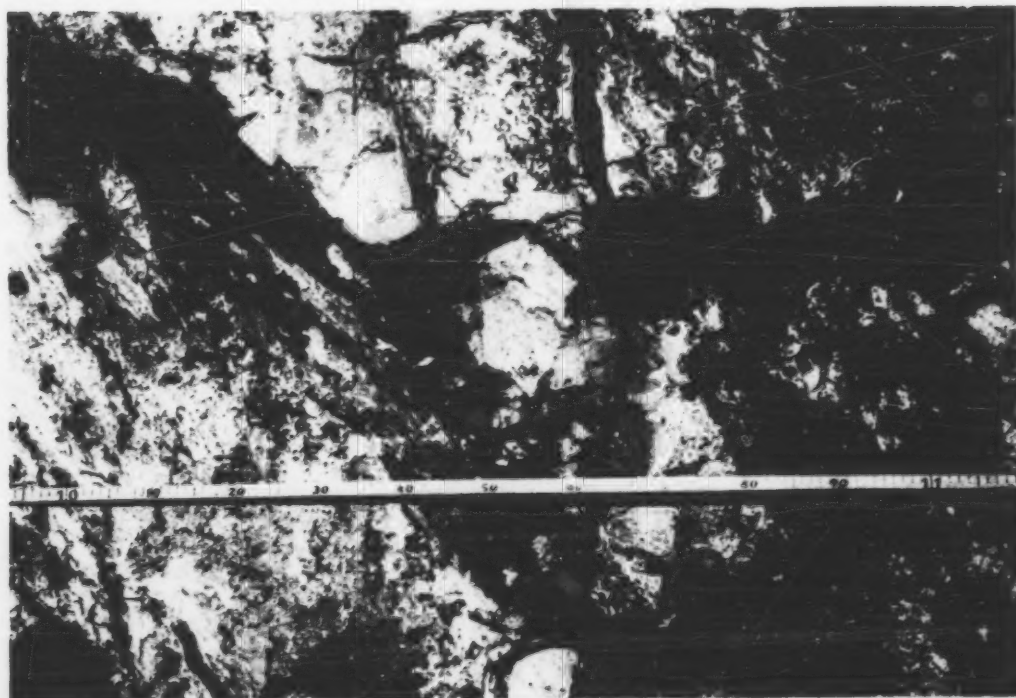


Plate IV. Silty sand infilling of fractures in rock mass



Moderately Kaolinized
Dacite Tuff Breccia With
Black Chalcocite Bands

Plate V. Moderately kaolinized dacite tuff breccia



Highly Kaolinized Dacite
Tuff Breccia

Plate VI. Highly kaolinized dacite tuff breccia



Plate VII. Highly kaolinized ore with chalcocite and chalcopyrite



Plate VIII. Kaolinized dacite tuff breccia in silty clay matrix



Plate IX. Sooty chalcocite - weak zone in ore body rock mass



Plate X. Kaolinized dacite tuff breccia in silty sand matrix

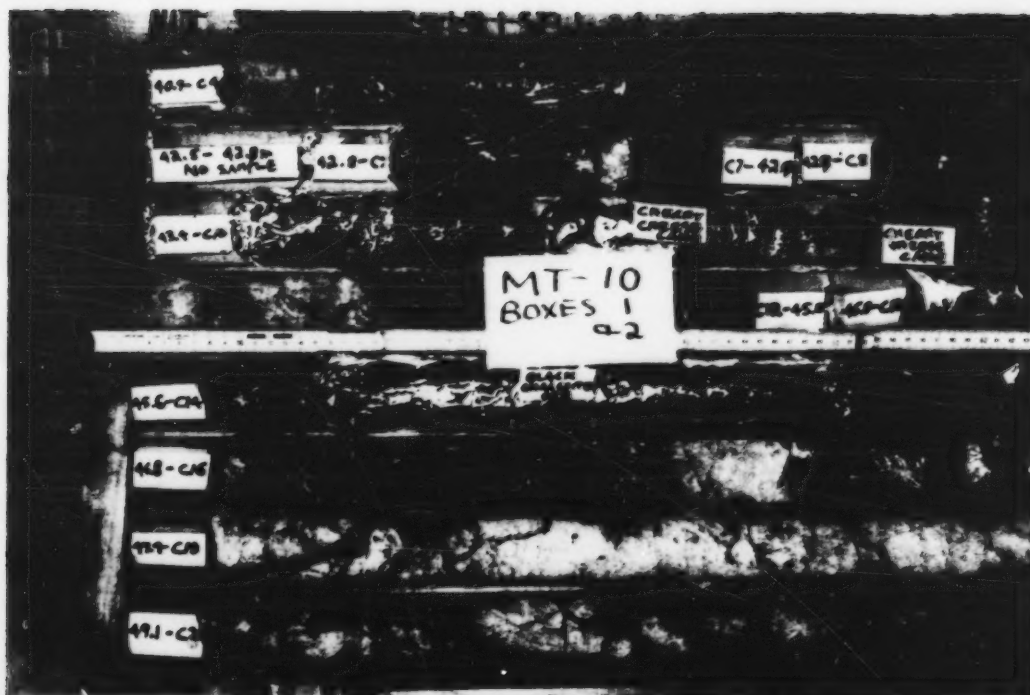


Plate XI. Part of rock core recovered at Borehole MT 10



Plate XII. Core from Borehole MT 12. Soil-like material is wrapped to prevent loss of moisture and minimize disintegration



Plate XIII. Chimney cave-in showing through at ground surface

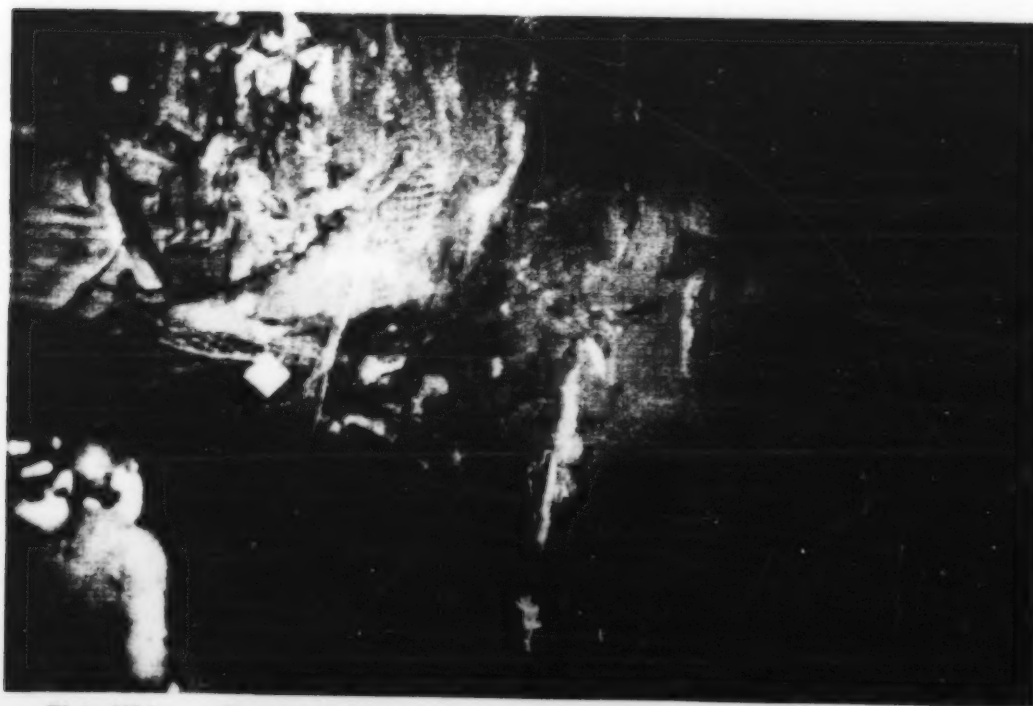


Plate XIV. Contact between ore body and overlying soil after removal of surface crown pillar

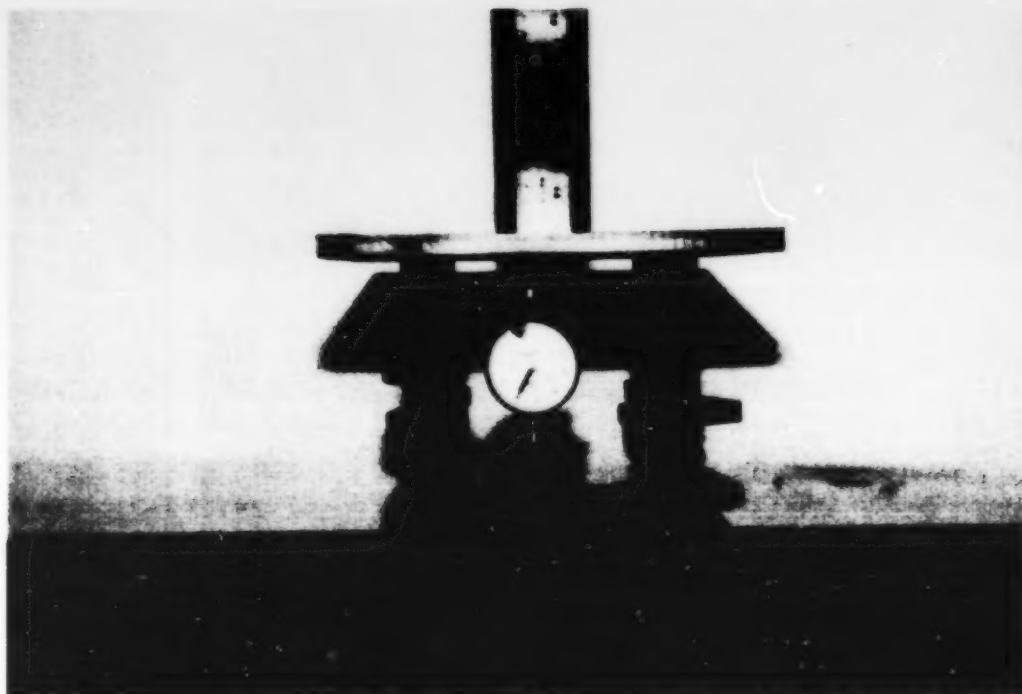


Plate XV. Instrument for measurement of surface crown pillar (SCP) deflection

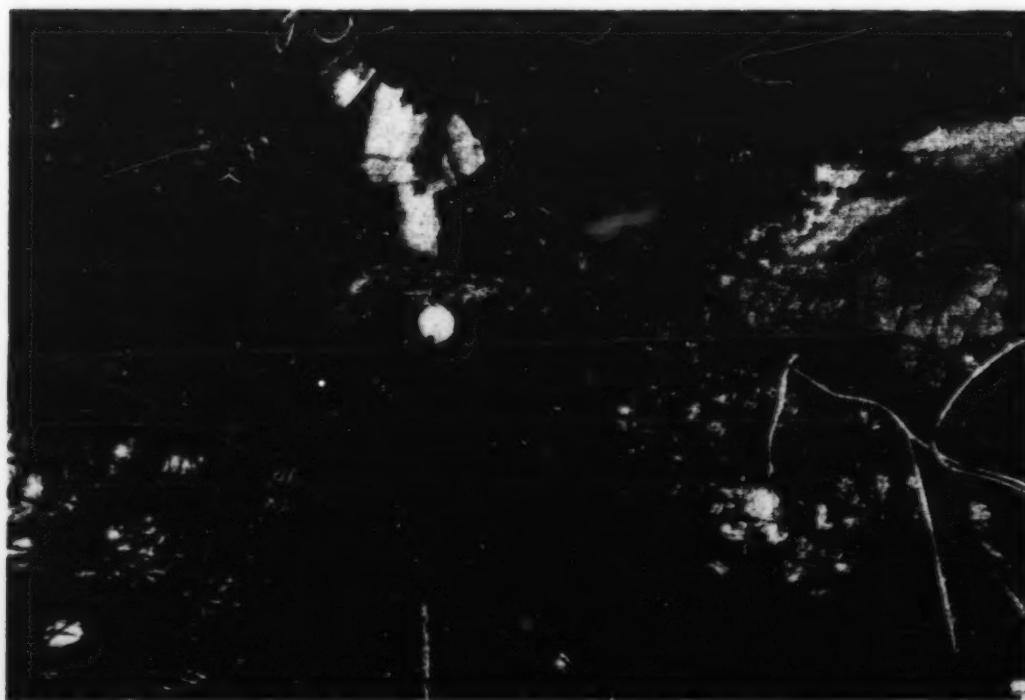


Plate XVI. SCP deflection monitoring instrument in position

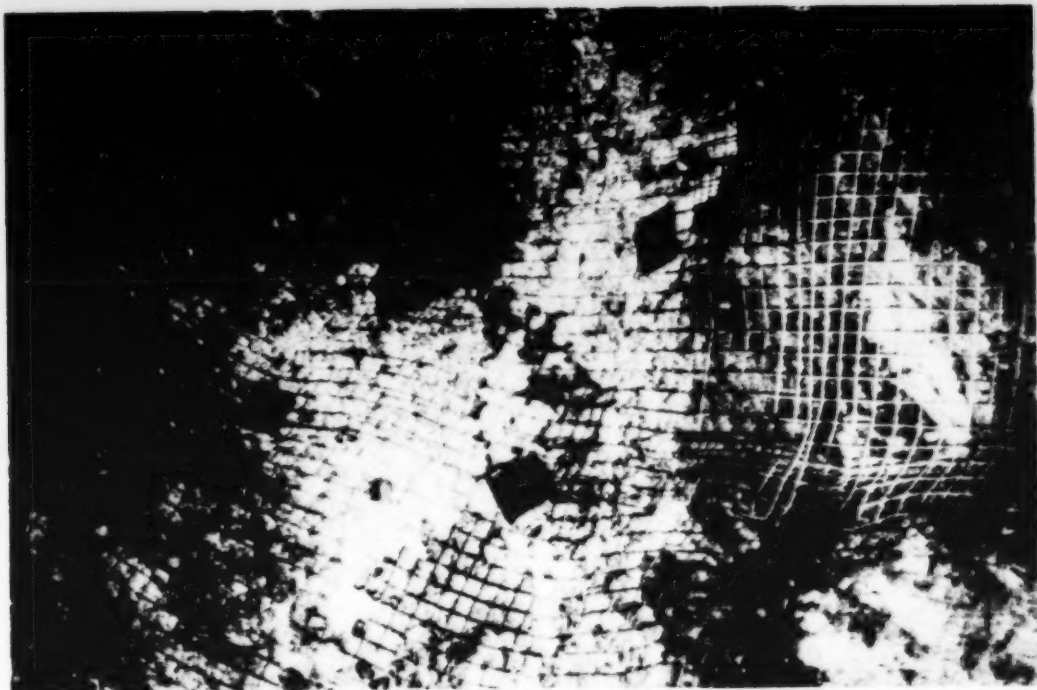


Plate XVII. Wire mesh and rock bolting of highly kaolinized pillar



Plate XVIII. Arching of sandy silt-silty sand till into dome shape above ore body rock mass

Page 10

ANSEER 05-2-10

LES MINES SELDRAIE ARMENTAGE

INTERSECTION

LASER 05-2-10-1

PT	ELE	NORD	QUEST	HI	AZ V.ARS
TP 1	5230.697	387.690	-1772.954	1.316	182.3500
TP 2	5232.106	387.807	-1774.663	0.900	189.1300

INPUT

ANGLES

NO	HOR-TP1	VER-TP1	HOR-TP2	VER-TP2
1	162.5000	38.3600	134.1300	45.1300
2	162.5100	35.5300	136.1000	61.2200
3	183.1100	38.3400	154.5600	40.3200
4	152.5900	38.3400	166.5200	38.2700
5	219.0800	38.3400	193.5100	34.1400
6	239.0900	43.5300	222.0900	37.1900
7	241.4000	51.5000	226.4600	45.3600
8	239.0100	58.4100	220.2500	51.2700
9	234.3200	76.1500	212.5500	76.2100
10	216.5100	76.3500	198.0700	73.2300
11	216.5100	64.3800	197.4800	62.3000
12	210.5900	50.1900	191.1500	47.5600
13	197.3600	48.4800	176.1800	47.5400
14	183.5100	45.3700	160.2900	50.4600
15	179.2300	62.2300	157.5100	63.4600
16	179.4500	61.2400	158.5000	82.1100
17	182.4100	67.0100	162.0800	67.3700
18	183.4100	58.2700	164.0200	57.1100
19	200.3600	59.2100	183.4800	58.2600
20	206.5100	69.4300	190.0700	63.2100
21	192.4000	61.4500	176.3300	61.2800

RESULTS

COORDONNEES

NORD	ELEVATION	QUEST	DIFF ENTRE Z et Z ₀
384.32	5236.40	-1772.08	-0.037
383.90	5234.68	-1771.97	-0.031
383.33	5237.52	-1773.39	-0.041
382.77	5238.42	-1774.32	-0.046
383.23	5239.02	-1776.66	-0.042
384.64	5238.74	-1778.63	-0.052
384.51	5237.86	-1779.33	-0.044
384.94	5235.35	-1778.03	-0.041
384.86	5233.02	-1777.33	-0.031
381.89	5236.10	-1777.72	-0.036
381.06	5237.94	-1778.41	-0.038
381.63	5238.03	-1778.96	-0.042
381.36	5236.94	-1775.28	-0.041
381.93	5235.37	-1773.60	-0.038
381.31	5235.04	-1773.17	-0.037
381.02	5233.13	-1773.23	-0.034
379.54	5233.51	-1773.83	-0.037
380.24	5237.00	-1773.77	-0.039
378.88	5237.71	-1776.73	-0.043
379.48	5235.50	-1777.59	-0.037
377.63	5237.63	-1775.69	-0.043

2202

Séquence des savages
1° Savages Arabes
2° Savages Nèf.
3° Savages GH.

TONNAGE SHORT: 36 T
TONNAGE TONS: 33 T
TONNAGE (GROSS WEIGHT): 2,226

LES MESSIAES

Les Mines Solbail
Jouilly, Québec

05-14-05 2-12-02

[illegible]

LES MINES SELBAIE

CHANTIER NO

RANG

BASE DE FORAGE

SECTION VALUE



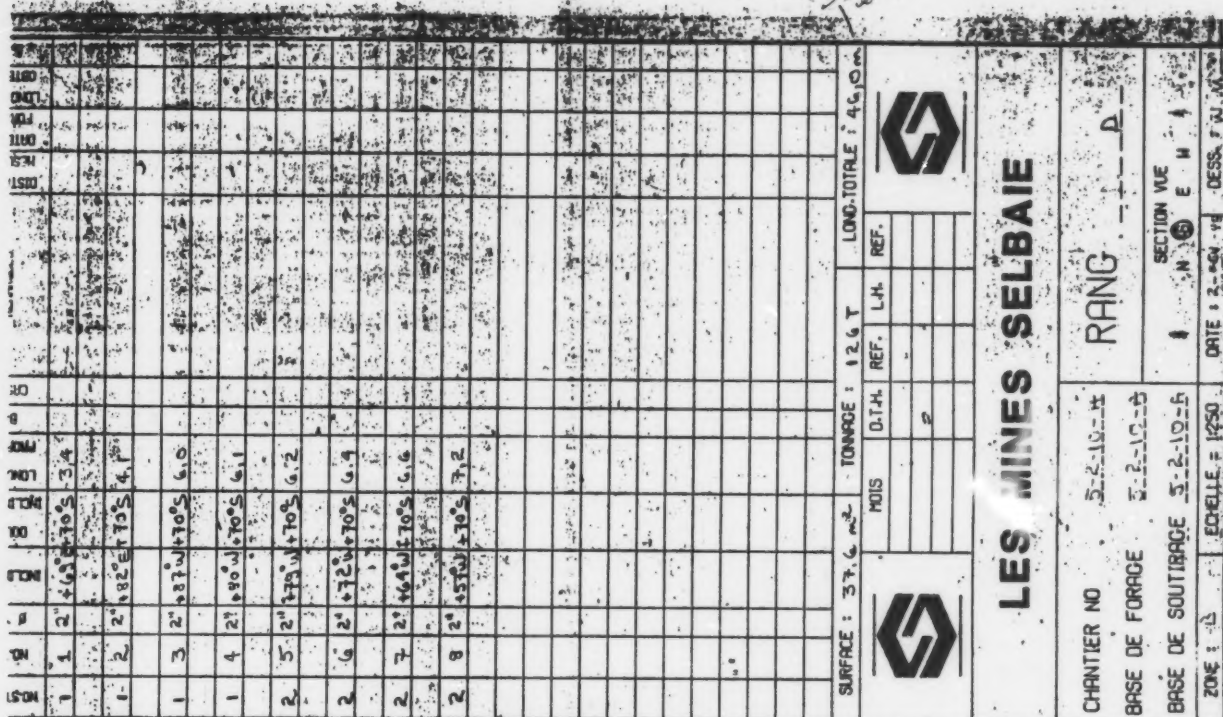
LES MINES SELBAIE

CHAN TIER NG

CHODURA

Page 10

B



LES MINES SELBAIE

CHANTIER NO

5-2-10-11

RANG

BASE DE FORAGE

15-2-15-4

4

BASE DE SOUTIEN

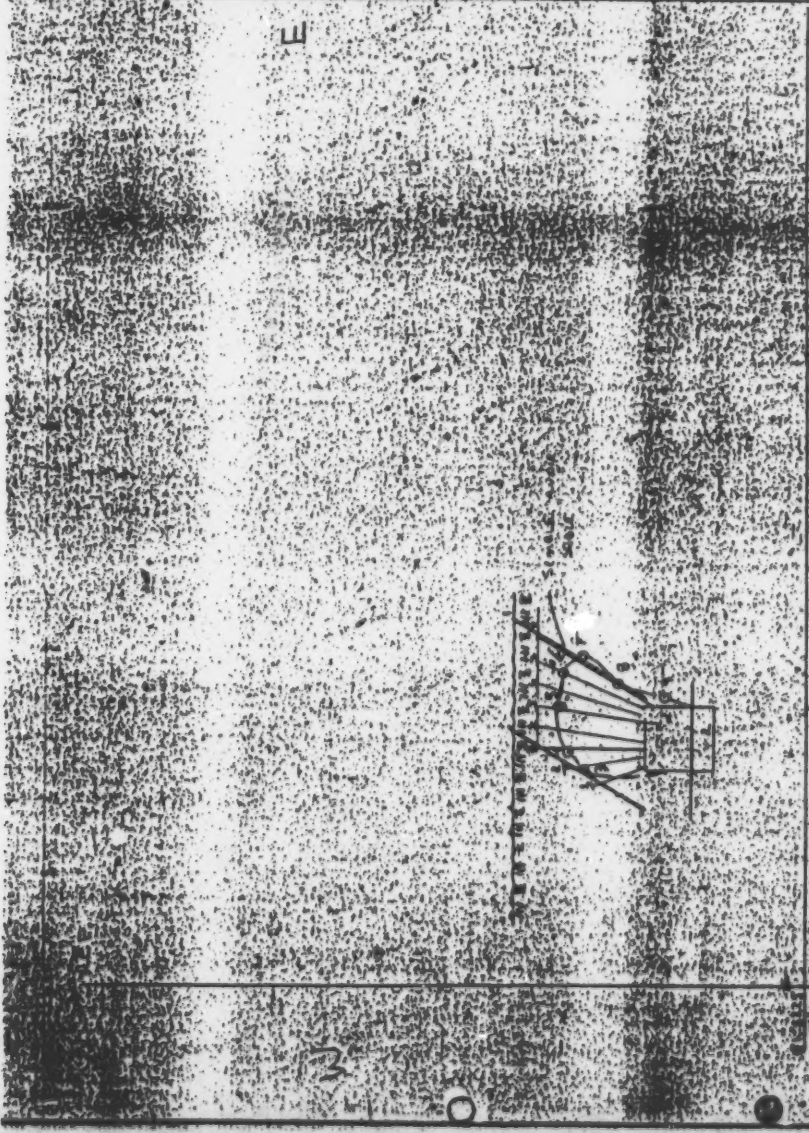
5-2-10-6

SECTION VUE

रु. : 3102

0521 = 3446
1250 = 1250

CV-49 DESS

[illegible]

LES MINES SELBAIE

CHANTIER NO	55104	RANG	SECTION N°
BASE DE FORAGE	1115		
BASE DE SOUTIRAGE	1115		



INSTRUMENT	ALTIMETER	# TEND	BOLIMERS	DOUBLE	BOLIMERS	ALTIMETER	PROF CODE	S.T.	CRSING	REMARKS	DESTINATION	DATE OF	FORMER	REMARKS
1	1	1	70° 40' S	70° 40' S	70° 40' S	70° 40' S	3.2							
2	2	2	81° 12' S	70° 40' S	70° 40' S	70° 40' S	4.6							
3	3	2	89° 00' S	70° 40' S	70° 40' S	70° 40' S	5.3							
4	4	2	91° 00' S	70° 40' S	70° 40' S	70° 40' S	6.0							
5	5	2	98° 00' S	70° 40' S	70° 40' S	70° 40' S	6.0							
6	6	2	93° 00' S	70° 40' S	70° 40' S	70° 40' S	6.3							
7	7	2	165° 00' S	70° 40' S	70° 40' S	70° 40' S	6.6							
8	8	2	99° 00' S	70° 40' S	70° 40' S	70° 40' S	7.7							

SURFACE : 39.2 m²

TONNAGE : 132 T

LONGITUDE : 46° 5'

MOIS

DATE

REF.

LONGITUDE

REF.

LONGITUDE

LES MINES SELBAIE

CHANTIER NO

2015-10-14

RANG

BASE DE FORAGE

●

BASE DE SOUTIEN

17-2

SECTION VUE

53

